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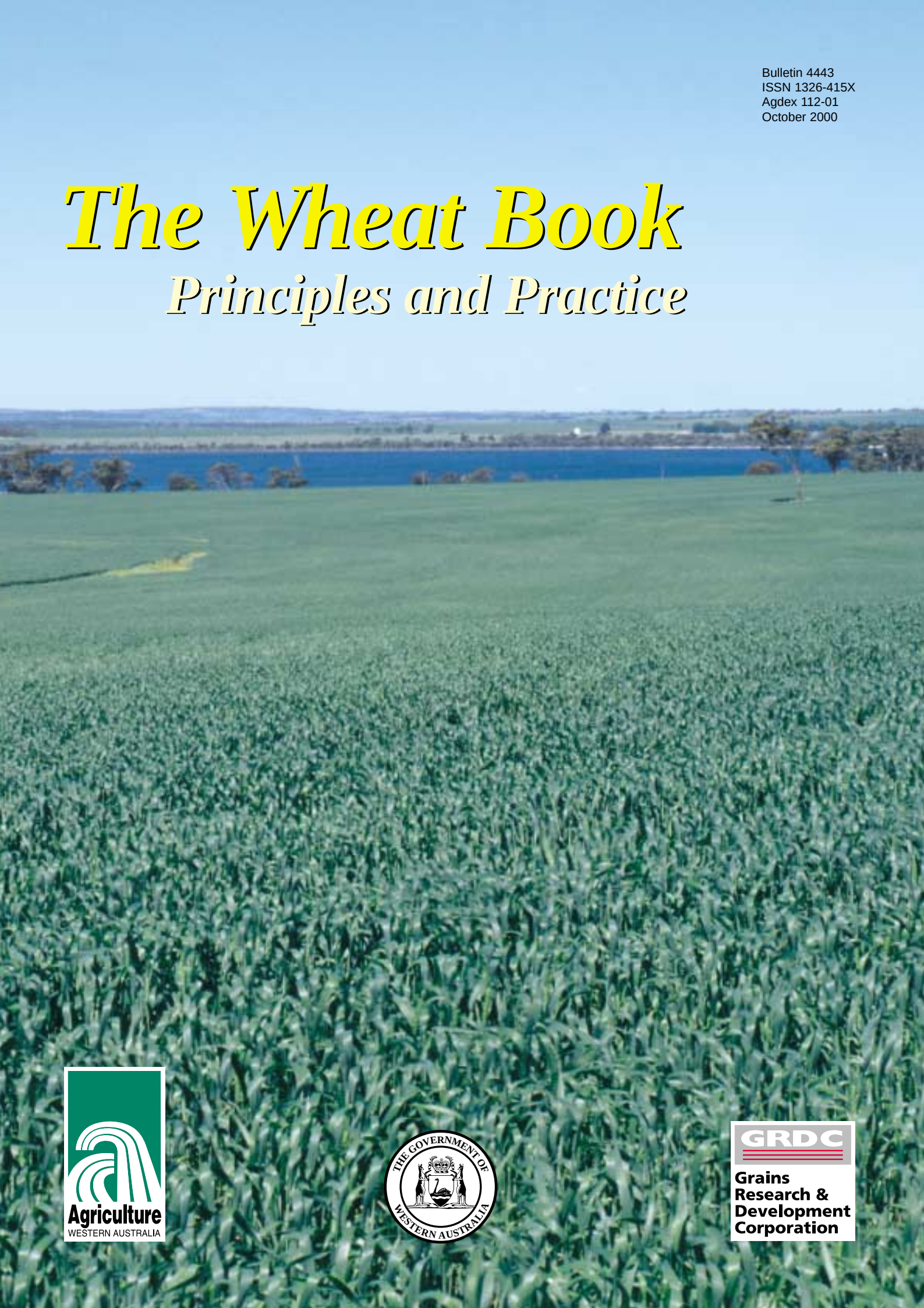
The Wheat Book

Principles and Practice



Agriculture
WESTERN AUSTRALIA

THE GOVERNMENT OF WESTERN AUSTRALIA

GRDC
Grains Research & Development Corporation

The Wheat Book

Principles and Practice

Compiled by W.K. Anderson and J.R. Garlinge

Agriculture Western Australia

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ACKNOWLEDGEMENTS

The second edition of The Wheat Book has been somewhat changed from the original edition. Some of the authors of the chapters of the first edition have moved on or were no longer available to revise their contributions. The editors and authors of the second edition acknowledge the original contributors, especially Michael Perry and Brian Hillman who edited the first edition. Some of the chapters in the second edition are revisions of the original chapters and in these cases the original authors are acknowledged at the start of each chapter.

There are some new chapters or sections on weed management, grain quality, marketing, durum wheat, feed wheat and triticale and several chapters have been considerably expanded. All chapters have been revised to include new information where applicable.

The reaction from readers of the first edition of The Wheat Book has indicated that major users have included consultants, company agronomists, undergraduate students, technical specialists in machinery companies, seed merchants and fertilizer companies, in addition to wheat growers. As a consequence we have decided to slightly change the emphasis of the second edition from "A technical manual for wheat producers" to "Principles and practice of wheat production" to accommodate this wider group of users.

The Grains Research and Development Corporation has funded the printing costs of the second edition. Most of the authors are employed by Agriculture Western Australia and most have contributed their time and talents as an extra-curricular activity.

W. K. Anderson and J. Garlinge (editors)

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CHAPTER ONE
ENVIRONMENT

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GLOBAL CIRCULATIONS AFFECTING WEATHER IN SOUTH-WESTERN AUSTRALIA

John Cramb
Western Australian Regional Office, Bureau of Meteorology

The climate of Western Australia's wheatbelt is strongly influenced by the position of a band of high pressure known as the sub-tropical ridge. An example is presented in Figure 1.1.

This ridge, which circles the hemisphere, separates the easterlies and the westerlies. The sub-tropical ridge moves north and south each year in response to the movement of the zone of maximum solar heating in the tropics. On average, the axis of the sub-tropical ridge is farthest south in the summer, well to the south of Albany. In winter it reaches its northern-most average latitude, near Geraldton.

The fundamental energy source that drives all atmospheric circulations is the unequal heating of the earth's surface by the sun. The earth's wind patterns and weather systems re-distribute energy from the hotter to the colder latitudes.

Warm, energy-laden air rises over the tropics, travels away from the equator in the upper atmosphere, then sinks back towards the surface forming the sub-tropical ridge. The sinking motion creates a warm, dry air mass, except in a relatively shallow layer close to the surface, where the character of the air is determined more by the nature of the surface over which it has been passing. The result is mostly fine weather under the sub-tropical ridge, frequently with clear skies, though cloud or fog may result if the trajectory of the air near the surface has allowed it to become sufficiently moist.

The sub-tropical ridge is not a continuous band, but rather consists of a number of discrete high pressure cells – the highs we usually see on the weather map – separated by areas of lower pressure. These low pressure areas may allow the ridge to be penetrated by air from the north or the south, to disturb the weather.

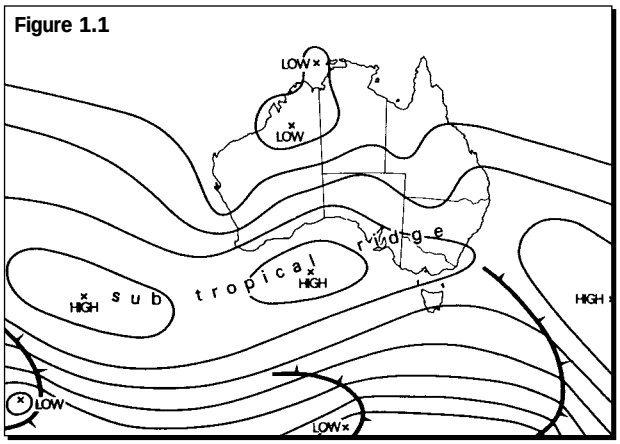
The easterlies

In a broad band extending north from the ridge, the air flow near the surface is generally from the south-east. These are the trade winds, which extend back into the tropics to complete the cycle, rising again with renewed energy. Over land, these winds are more variable in direction and are often referred to as simply 'the easterlies'. This is the normal regime that prevails over the wheatbelt throughout the summer and over the northern wheatbelt for much of the winter as well.

The easterlies assume the characteristics of the surface over which they have been passing, usually becoming hot and dry in the summer and cool and dry in the winter, but with variations well know to those who live in the area. Above the surface, the atmosphere is generally stable so fine weather is the norm but occasional disturbances occur.

Some of these disturbances originate deep in the tropics – such as decaying tropical cyclones moving south. More common are the 'upper air disturbances', which originate from upper-level westerlies, and the 'cut-off lows', which are lows that have either developed downwards from upper-air disturbances or else moved out of the surface westerlies further to the south.

Figure 1.1



A typical summer weather map showing the sub-tropical ridge to the south of Western Australia.

Even more common in the wheatbelt, however, are those disturbances forming in the west coast trough, which develops during the warmer months because of the contrast in air density across the west coast, as the air is heated over the land and cooled over the sea. The west coast trough is associated with most of the weather changes throughout the warmer part of the year.

The westerlies

To the south of the sub-tropical ridge, the air flow varies mostly between north-west and south-west. Because of their maritime origin, the westerlies are usually cool and moist as they reach our coast, though they become drier as they progress inland.

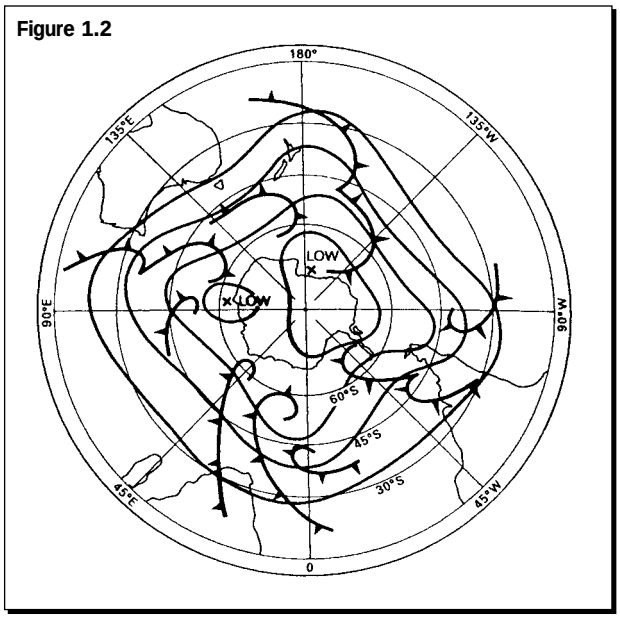
Atmospheric disturbances are much more common in the westerlies, with cold fronts passing through perhaps twice a week or more in winter. The density contrasts in the westerlies form a ready energy source for the development of depressions, and of the cold fronts which mark the boundaries of new bursts of cold air.

The main process by which the atmosphere achieves the necessary energy transfer from north to south across the westerly zone is different to that used in the tropics. Because of the rotation of the earth, the large-scale convection cells that operate between the deep tropics and the sub-tropical ridge are unable to extend all the way to the poles. Instead, the westerly flow above the surface meanders, forming giant waves which are called planetary waves or simply long waves. Energy-laden air, warm and frequently moist, is transported pole-ward ahead of the long wave troughs, while cold air moves north to the west of the troughs.

The waves can often be detected in the pressure patterns on the surface weather map for the hemisphere,

GLOBAL CIRCULATIONS AFFECTING WEATHER IN SOUTH-WESTERN AUSTRALIA *(continued)*

Figure 1.2



A representation of upper level wind flow around the southern hemisphere. A long wave trough is positioned just to the west of Western Australia.

particularly if pressures are averaged over a few days. However, the waves are really to be found in the stronger westerly flow at higher levels in the atmosphere, where they are usually easy to distinguish on charts of wind flow or pressure pattern.

There are normally about three or four long waves around the southern hemisphere. There is no stable configuration, so the pattern keeps changing. They usually move from west to east, but occasionally move the other way, particularly if the spacing between the troughs becomes large. They almost always move more slowly than the individual cold fronts and can sometimes persist in an area for weeks. Because they have a strong steering influence on the fronts, they often give a useful indication of the likely weather some days ahead.

Thus, if there is a long wave trough near the west coast of Western Australia in winter, it is likely that cold fronts will continually move up towards the area, causing persistent rainfall events over the wheatbelt. When there is a long wave ridge in our longitudes, individual fronts, if they arrive at all, are likely to be relatively weak.

Figure 1.2 illustrates a four-wave pattern in the upper level flow around the southern hemisphere, with one of the long wave troughs just to the west of Western Australia and a long wave ridge over eastern Australia. The possible surface positions of cold fronts are marked.

Even though the westerlies spawn most of the rain-generating disturbances affecting the wheatbelt, those systems that produce the greatest rainfalls usually derive their moisture from the tropics. Warm air can hold much more water vapour than cold air. This is basically why it rains at all – air that is forced to rise can be cooled until its moisture condenses and falls out.

A good rain producing system will have a combination of the following conditions in as great a measure as possible:

- The air will be moist through a great depth of the atmosphere;
- The lifting process will be strong, and
- The lifting process will be sustained.

The first condition is found particularly in northerly and north-westerly air-streams above the surface, with much water vapour of tropical origin being brought south, ahead of a disturbance such as a cold front approaching from the west. This southward movement of tropical air may be rapid.

Strong lifting is found particularly near the deep lows and strong fronts that form the westerlies. The third ingredient – prolonged lifting – is usually found in large and/or slow-moving systems. Fronts whose progress has been arrested or cut-off lows north of the ridge axis are especially favourable, even though they may not be very strong.

Long range weather forecasting

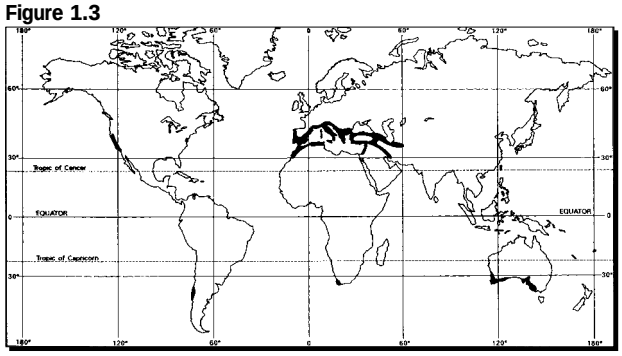
The motions of the atmosphere are particularly complex, and make the task of long range forecasting particularly difficult. Computer models, working with enormous amounts of meteorological data such as temperatures, humidities and pressures from around the globe can solve the equations describing the motions of the atmosphere. These models are continuing to improve our ability to forecast the weather up to a few days ahead.

Longer range forecasting, months or seasons ahead and extending out to the scale of decades is receiving intense scientific effort. It is crucial that longer-term climate trends be investigated, particularly those that may result from human activities. We are currently unable to give clear answers to the important questions concerning the likely nature of long-term climate changes in specific areas such as the wheatbelt. Unfortunately, such are the complexities of the problems involved, it could well be many years yet before this can be done with confidence.

■ CLIMATE IN RELATION TO AGRICULTURE IN SOUTH-WESTERN AUSTRALIA

John Cramb
Western Australian Regional Office, Bureau of Meteorology

Figure 1.3



Mediterranean climates of the world.

Located in the middle latitudes (30 to 40°S) the agricultural areas of south-western Australia have a dry-summer sub-tropical (Mediterranean) climate similar to the Mediterranean basin, southern California, Chile and the western tip of Cape Province, South Africa (see Figure 1.3).

Weather patterns in these regions are dominated by the influence of the dry, subsiding air masses of the sub-tropical ridge. In summer, as the ridge moves poleward, the climate has the characteristics and consistency of the dry tropics; while in winter it features the changeability of weather from the passage of the cyclonic circulations and cold fronts embedded in the westerlies.

The three characteristics of all Mediterranean climates (and expressed particularly strongly in south-western Australia) are:

- A concentration of the rainfall in the winter season, with the summers being nearly, or completely dry;
- Warm to hot summers and mild winter; and
- High solar radiation, especially in summer.

The most important climatic elements influencing wheat production are rainfall, solar radiation and temperature. These, both directly and indirectly (for example, through waterlogging), determine crop growth and grain yield.

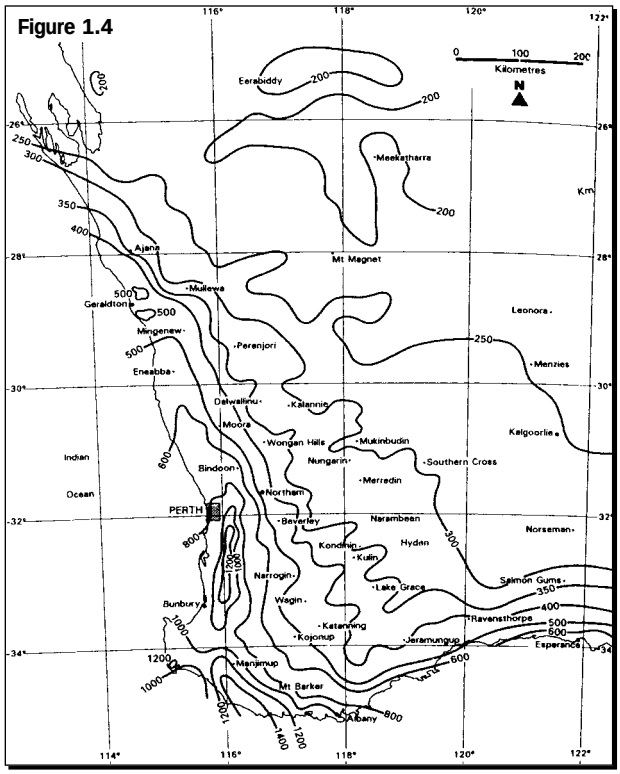
Rainfall

Annual rainfall decreases rapidly from about 1200mm on the south and south-western coasts to about 250mm at the inland limit of agriculture. The distribution is shown in Figure 1.4.

Most wheat is produced in areas with less than 500mm annual rainfall and over 40% of production is from areas receiving 325mm or less.

Rainfall distribution peaks sharply in mid-winter, especially in the west and north-west wheatbelt. Geraldton and Wongan Hills receive over 80% of their annual rainfall in the winter growing season. Usually, 60 to 70% of annual rainfall is received between May and October, the proportion of growing season rainfall decreasing to the east. The growing season rainfall for certain wheatbelt centres is listed in Table 1.1.

Figure 1.4



Distribution of annual rainfall in south-western Australia.

Table 1.1 – Annual growing season (May to October) rainfall for some major centres in the wheatbelt of western Australia.

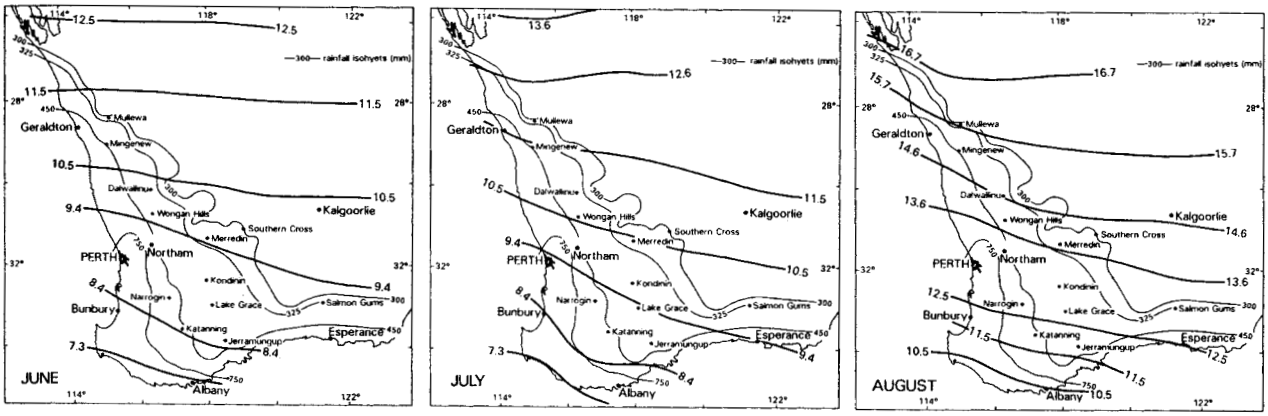
Locality	Annual (mm)	May to Oct (mm)	May to Oct (%)
Geraldton	370	395	84
Mullewa	337	253	75
Mingenew	414	338	82
Wongan Hills	387	297	77
Bencubbin	319	211	66
York	454	366	81
Merredin	326	231	71
Hyden	334	225	67
Katanning	482	362	75
Salmon Gums	342	209	61
Albany	937	709	76
Esperance Downs	490	334	68

The concentrated winter rainfall pattern means that waterlogging can be severe in winter, nutrients can be readily leached as water penetrates below the root zone, and that recharge of watertables may be difficult to prevent, particularly under shallow rooted annual species.

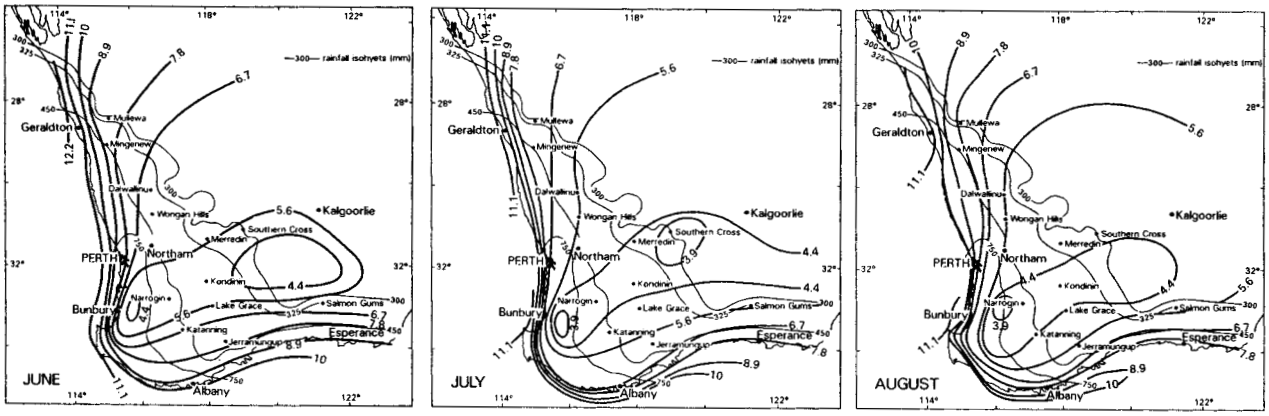
■ CLIMATE IN RELATION TO AGRICULTURE IN SOUTH-WESTERN AUSTRALIA *(continued)*

Figure 1.5

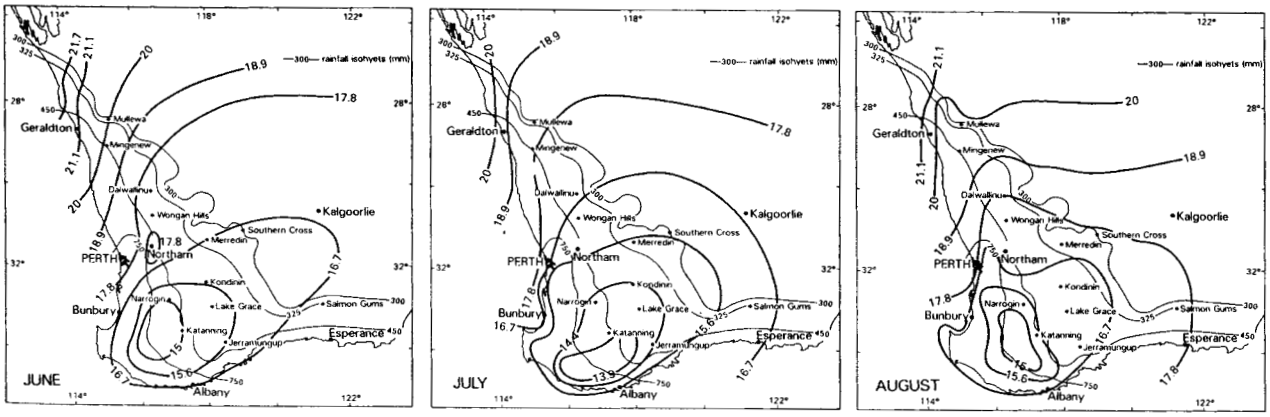
Solar



Minimum



Maximum



Mean monthly solar radiation (MJ/m²/day), minimum and maximum temperature (°C) for June, July and August.

■ CLIMATE IN RELATION TO AGRICULTURE IN SOUTH-WESTERN AUSTRALIA *(continued)*

Rainfall has had another indirect, but important, influence on the agriculture of the region – salt. The large amounts of salts stored in the subsoils of the wheatbelt are of maritime origin. The salts have a composition similar to that of sea water. Over much of the wheatbelt between 20 and 40 kg of salt is added to each hectare from rainfall every year.

Without the drainage systems to return this salt to the oceans, it has accumulated in the subsoils and is now causing salinization of parts of the landscape where rising watertables (caused by clearing) bring the saline groundwaters to the surface.

Solar radiation

Solar radiation is the second most important climatic element after rainfall, because it determines the temperature and evaporation regimes which drive plant growth. Figure 1.5 illustrates the pattern of solar radiation received during the winter months of June, July and August. At 8 to 10 megajoules per square metre per day (MJ/m^2/day), solar radiation is unlikely to limit crop growth, especially as crop and pasture leaf areas are low in winter.

The solar energy reaching the ground in summer may reach 30 MJ/m^2/day due to the elevation of the sun, the clear atmosphere and cloud-less skies. These are amongst the greatest radiation loads received at the earth's surface and are one reason for the productivity of irrigated summer crops in regions of Mediterranean climates.

Temperature

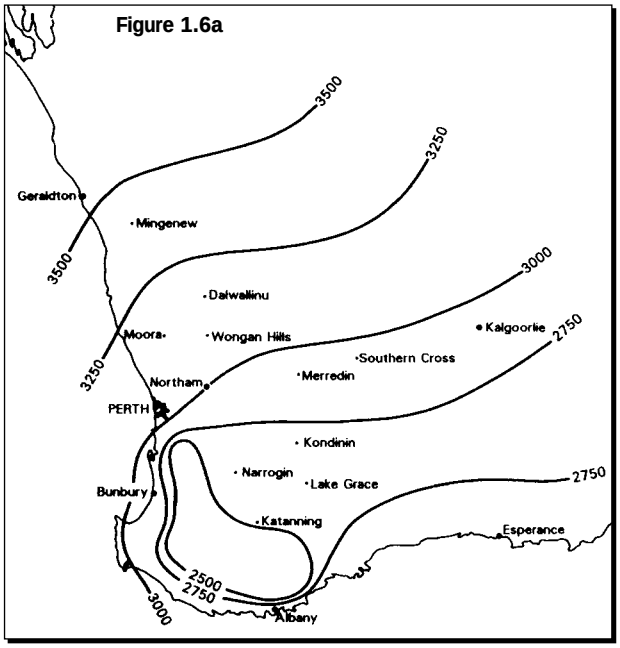
Mean annual temperatures for the wheatbelt follow closely the trends of solar radiation, however, winter temperatures are moderated close to the coast by the Indian and Southern Oceans. Coolest temperatures occur in the southern and eastern wheatbelt (Figure 1.5) where mean temperatures are between 10 and 12°C for the winter months. Minima for the same period are 4 to 5°C, and maxima 14 to 16°C. The optimum temperature for wheat growth is about 25°C.

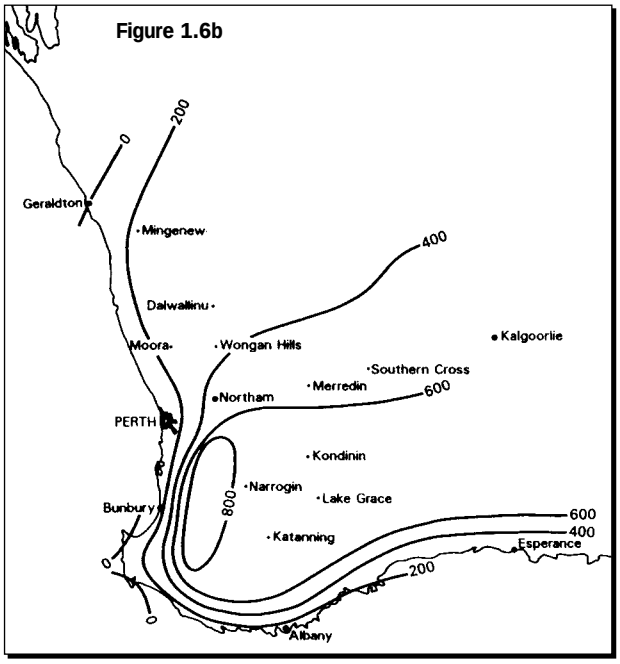
Although mean temperatures indicate the suitability of the environment for crop growth, processes such as leaf growth, tillering and the progress of plant development are often closely related to the *Accumulated* temperature. This is expressed in °C.days (degree days) and is explained in Chapter 3. Basically, it is the sum of the mean temperatures for each day.

Figure 1.6 shows the accumulated temperature or 'growing °C.days' for May to October. Accumulated temperatures are useful for comparing growing environments. From the meteorological tables in the Appendix, it is possible to calculate accumulated temperatures for many other purposes.

Low temperatures can stimulate the development of some wheats. Accumulated temperatures below 10°C can be a measure of the ability of the environment to satisfy a plant's low temperature requirement.

In Western Australia, temperatures are low enough to stimulate most winter wheats to flower but the season is not long enough to allow them to reach their full yield potential.





a. Growing °C days (base 0°C), and b. vernalizing °C days (accumulated temperature below 10°C for April to October).

Synoptic events

During winter, there are several synoptic events (that is, weather occurring over several days) which are of particular importance to agriculture. These are shown in

CLIMATE IN RELATION TO AGRICULTURE IN SOUTH-WESTERN AUSTRALIA *(continued)*

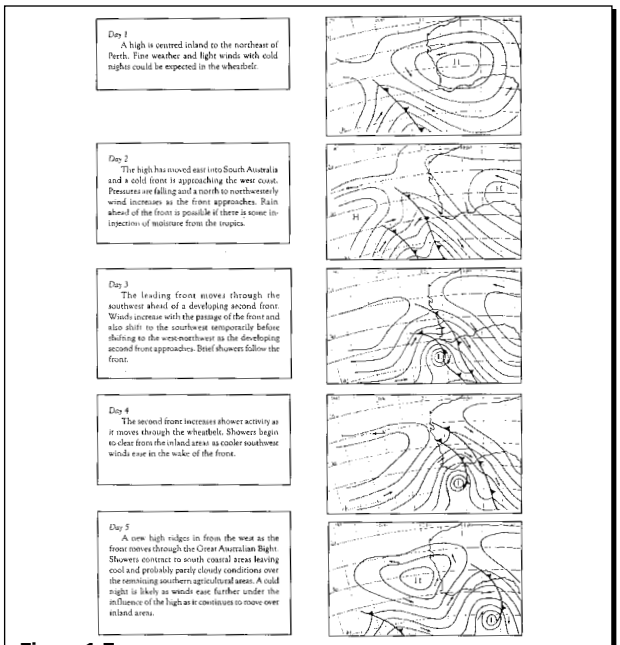


Figure 1.7

Typical series of daily weather charts showing events during the passage of cold fronts.

the series of daily pressure maps in Figure 1.7, illustrating a typical sequence of weather events.

The most obvious is the passage of cold fronts over the southern part of the state during days 3 and 4 of the sequence. As explained previously, this is the main source of rainfall during winter and spring.

Another aspect is the potential for wind erosion. If the sequence of events in Figure 1.7 occurs in late autumn or early winter, the situation on Day 2 could present a risk of wind erosion. Strong northerly winds can be generated as the approaching front increases the pressure gradient between itself and the high to the east. If the land has minimal plant cover from grazing pressure, or from dry seeding, then susceptible soils will suffer wind erosion. Fine particles and nutrients will be lost as dust and larger soil particles can move across paddocks, piling up along fence or tree lines.

In late winter and spring, the last day of the sequence increases the likelihood of frost. The preceding days (days 3 and 4) are likely to have been cloudy, wet and cool or cold. As the new high establishes itself the night will probably be cloud-free and there will be no or light winds. Under these conditions, the land surface will cool rapidly through radiation of thermal energy to space.

The combination of preceding cool days, cold southerly airflow and clear skies can produce low temperatures. Cold air will tend to move downslope and accumulate in the lowest parts of the landscape, often producing frost as water vapour freezes on plant surfaces. In severe cases, water inside plant tissues freezes and bursts the cells.

Frost is an important agricultural risk and is covered in more detail in Chapter 7.

Climatic sub-division of the wheatbelt

The primary sub-division of climate for the south-west of Western Australia is a north-south separation approximately at right angles to the western coast. A second sub-division can be made on the pattern of rainfall isohyets parallel to the coast.

This map (Figure 1.8) is similar to the regional sub-divisions adopted for Agriculture Western Australia's crop variety recommendations.

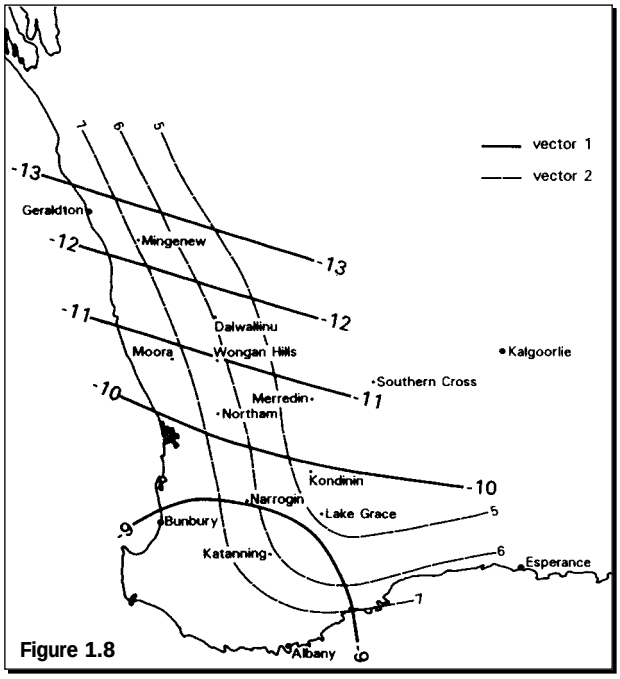


Figure 1.8

A sub-division of the south-east of Western Australia according to climatic features.

Australian climates used for wheat production

It is often assumed that wheat production throughout southern Australia takes place in a relatively similar environment: so that technology and production systems might be readily transferred. This is not the case.

Although the westerlies dominate in the south, the climate of eastern Australia is more complex. Winter rainfall from the westerlies is supplemented by summer rainfall from moist air masses from the Pacific Ocean. Rainfall grades from strongly winter-dominant in the west, through a uniform, all-year-round distribution in Victoria and southern New South Wales, to strongly summer-dominant in the north. The range is illustrated in Figure 1.9.

The Australian wheatbelt can be divided into three regions: a southern winter rainfall region, a northern region of summer-dominant rainfall and a south-eastern region of high (greater than 550mm), and evenly distributed rainfall.

GLOBAL CIRCULATIONS AFFECTING WEATHER IN SOUTH-WESTERN AUSTRALIA *(continued)*

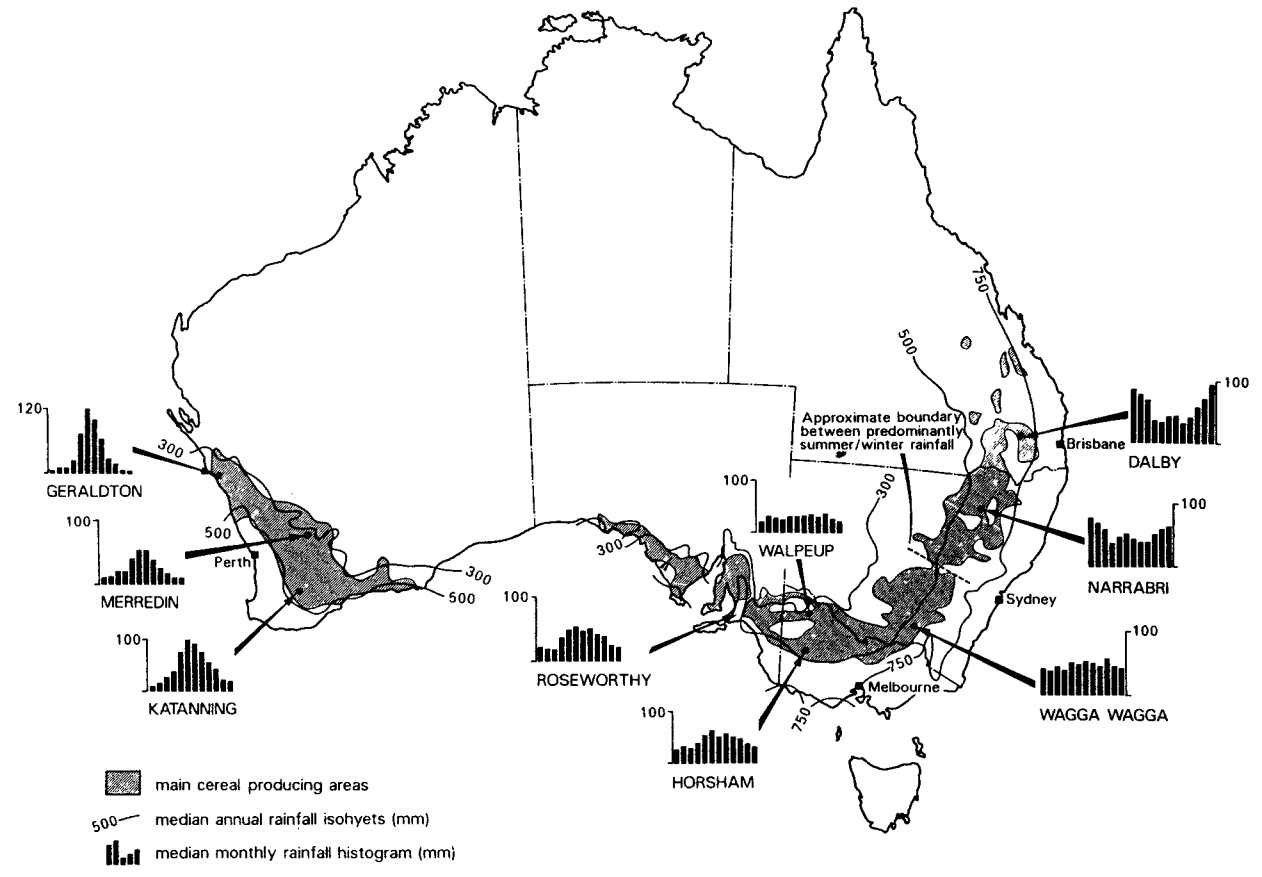
The winter rainfall region produces about 70% of Australia's cereals; and includes Western Australia, South Australia, Victoria and southern New South Wales. The characteristic winter peak is most extreme in the west where Geraldton and Wongan Hills receive 80 to 85% of the annual rainfall in the growing season. More typically, 60 to 70% of rainfall is received in the growing season, (Merredin 66%, Clare 61 per cent, Walpeup 59% and Horsham 58%). Mid-winter temperatures are mild (12 to 15°C day / 5 to 8°C night) and mid-winter radiation levels low (9 to 11 MJ/m^2/day).

The summer rainfall region extends from central New South Wales to Queensland and accounts for about 25% of cereal production. Rainfall is greater and increases in both amount and summer dominance to the north. Dubbo, for example, receives 531mm, with 42 per cent falling in winter, Narrabri 662mm (38%), Dalby 614mm (29%) and Biloela 705mm (19%).

Mid-winter temperatures are higher (15 to 19°C day / 8 to 12°C night) than in the southern region except at high elevation. Radiation frosts after ear emergence may cause severe damage and planting times are adjusted to avoid flowering during the period of greatest risk of frost.

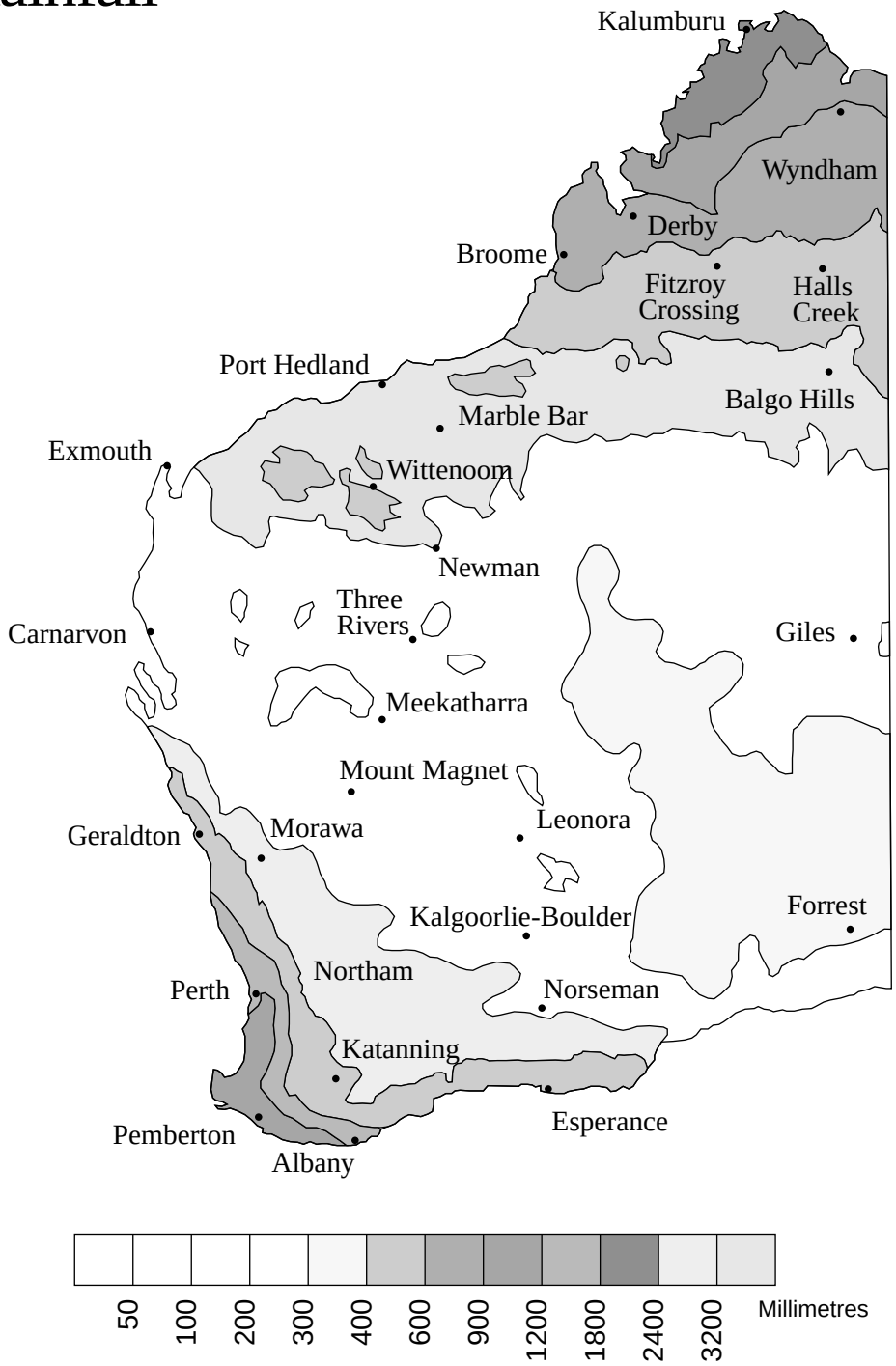
The south-eastern region, which lies to the south and east of the present wheatbelt, is high rainfall (over 550mm) with significant amounts in both summer and winter. This region produces less than 5% of Australia's wheat.

Figure 1.9



Rainfall amount and distribution for the wheatbelt of western, southern and eastern Australia.

Average Annual Rainfall



Based on a standard 30-year climatology (1961 to 1990)

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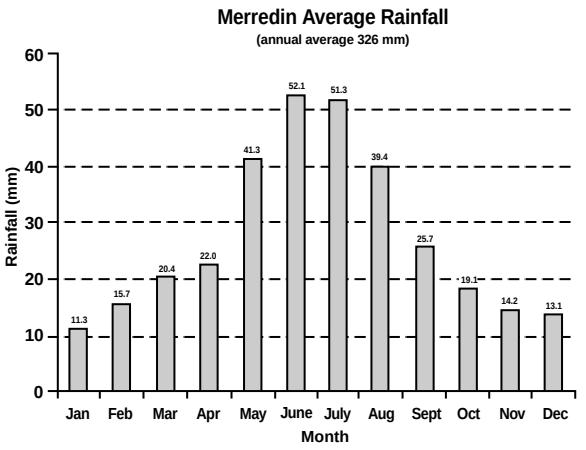
■ CLIMATE VARIABILITY AND SEASONAL FORECASTING

Joe Courtney
Western Australian Regional Office, Bureau of Meteorology

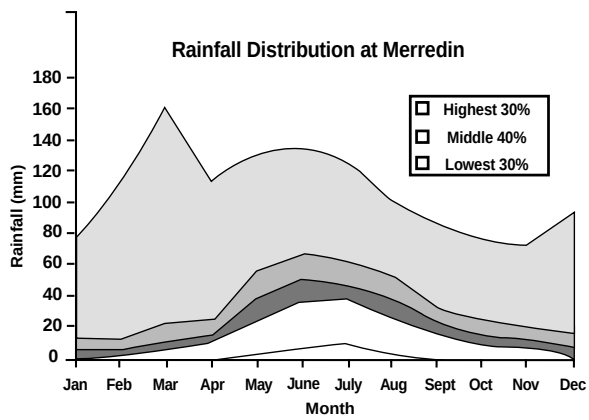
Most people tend to think of averages when talking about the climate of an area. The annual average rainfall map (opposite) shows the geographic distribution of average rainfall and a site's monthly averages (Figure 1.10a) indicate the general distribution during the year. This is a good starting point but sometimes more important is knowing the variability of the climate from one year to the next. The distribution of rainfall in each month can be expressed using deciles or percentiles which show the chance of getting certain amounts of rainfall (Figure 1.10b). For example, at Merredin in July when the median is 48mm, in the driest 30% of July months rainfall is less than 37mm and in the wettest 30% of July months rainfall is at least 59mm. The lowest reading is 9mm and the highest is 127mm.

Figure 1.10a



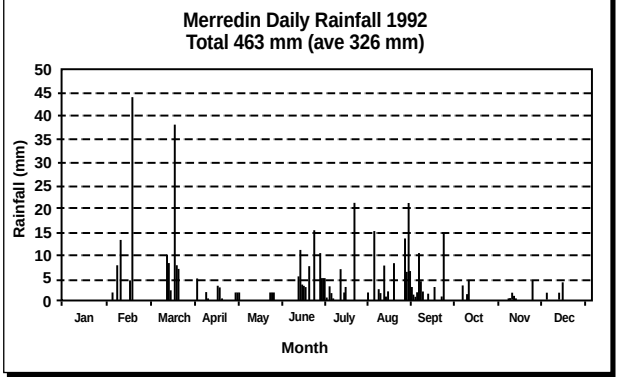
Average annual rainfall at Merredin.

Figure 1.10b



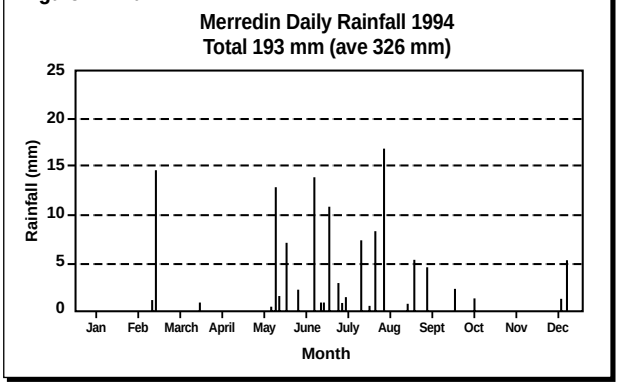
Monthly rainfall distribution at Merredin.

Figure 1.11a



Daily rainfall at Merredin in 1992.

Figure 1.11b



Daily rainfall at Merredin in 1994.

However, this is still looking at rainfall on a monthly basis. The timing and amount of daily rainfall is probably a better guide in determining the characteristics of a season. For example, the years 1992 and 1994 show completely different rainfall patterns and would require different management strategies to optimise property production (Figure 1.11).

Mechanisms that modify the seasons

We are quite familiar with the causes of day to day weather patterns such as the movement of highs, lows and cold fronts. However, trying to explain the variations of the seasons one year to the next has been far more complicated.

While there is still a long way to go, research in the past 20 years has uncovered some of the influences on our seasonal weather patterns. Variations are linked to the three oceans surrounding the continent (Indian, Pacific and Southern). The effects of each of these wax and wane, interacting with each other, making each year different from the last. Three identified effects are known as the El-Nino Southern Oscillation (ENSO) in the Pacific Ocean, the Indian Ocean Dipole, and a recent discovery of yet to be determined significance, the Antarctic Circumpolar Wave in the Southern Ocean. Each involves both the atmosphere and ocean acting together and affecting each

CLIMATE VARIABILITY AND SEASONAL FORECASTING

(continued)

other. These effects, together with others less well known or yet to be discovered, combine to be responsible for producing such a variable climate in Australia.

However, we are still limited in our ability to predict important seasonal features such as the timing of the first significant cold front that is often responsible for the break of season.

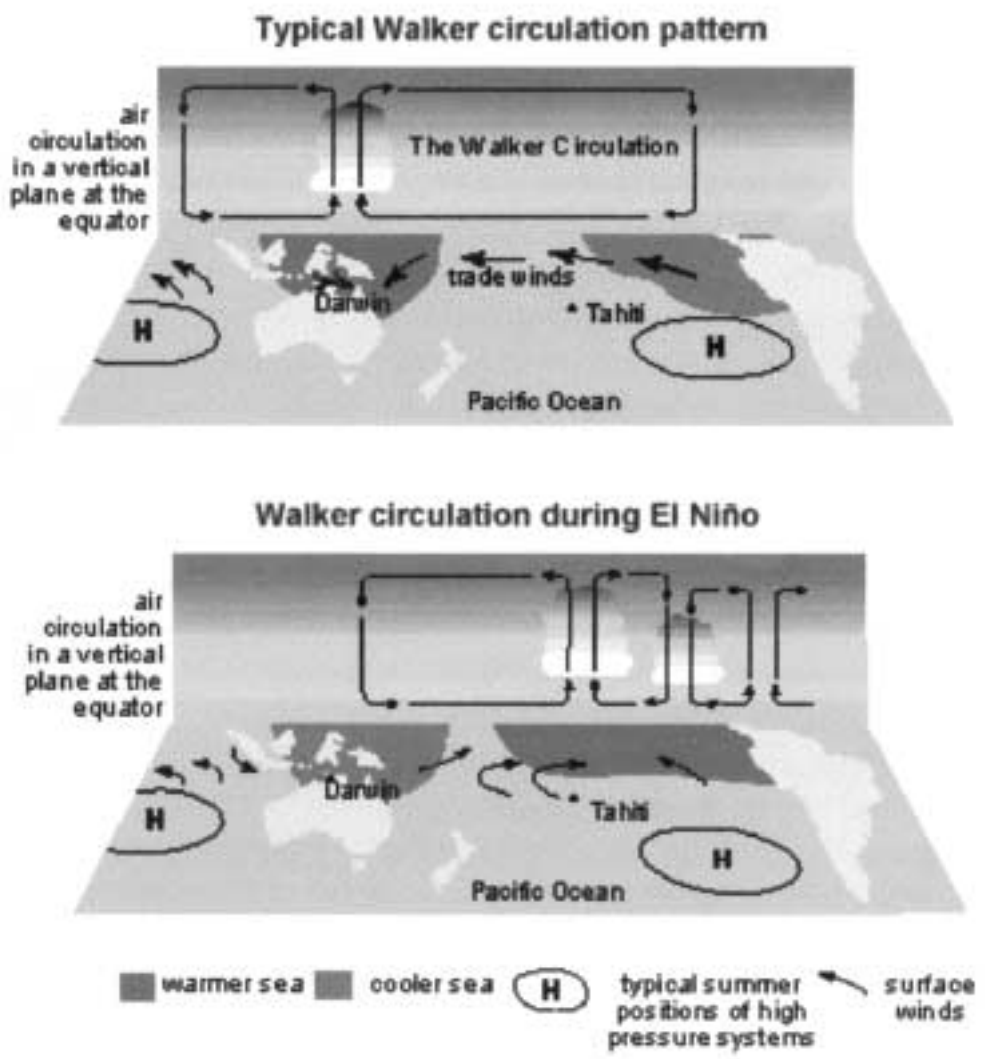
El Nino – Southern Oscillation

El Nino translates from Spanish as 'the boy-child'. Peruvian fisherman originally used the term, a reference to the Christ child, to describe the appearance, around Christmas, of a warm ocean current off the South American coast.

Nowadays, the term El Nino refers to the extensive warming of the central and eastern Pacific that leads to a major shift in weather patterns across the Pacific (Figure 1.12). El Nino events are associated with an increased probability of drier conditions particularly in eastern Australia.

Of the three factors listed above, ENSO is the most studied, best known and the most important feature for Australia's rainfall patterns. El Nino affects many parts of the globe, and is particularly significant for northern and eastern Australia. Its focus is the tropical Pacific Ocean where big changes can occur that involve both the atmosphere and the ocean interacting and affecting each other. These changes oscillate irregularly between two main states: El Nino and La Nina. These extreme events last for about 12 to 18 months with autumn often being the

Figure 1.12



Schematic diagram showing the major ENSO patterns.

■ CLIMATE VARIABILITY AND SEASONAL FORECASTING

(continued)

transition period, although the 1990s has witnessed an above average number of El Ninos, some in succession.

Changes to the atmosphere and ocean circulation during El Nino events include:

- Warmer than normal ocean temperatures across the central and eastern tropical Pacific Ocean.
- Increased convection or cloudiness in the central tropical Pacific Ocean – the focus of convection migrates from the Australian/Indonesian region eastward towards the central tropical Pacific Ocean.
- Weaker than normal (easterly) trade winds.
- Low (negative) values of the SOI (Southern Oscillation Index).

The term La Nina refers to the extensive cooling of the central and eastern Pacific Ocean (note: the term 'La Nina' has only recently become the conventional meteorological label for the opposite of El Nino). In Australia (particularly eastern Australia), La Nina events are associated with increased probability of wetter conditions.

Changes to the atmosphere and ocean circulation during La Nina events include:

- Cooler than normal ocean temperatures across the central and eastern tropical Pacific Ocean.
- Increased convection or cloudiness over tropical Australia, Papua New Guinea, and Indonesia.
- Stronger than normal (easterly) trade winds across the Pacific Ocean (but not necessarily in the Australian region).
- High (positive) values of the SOI.

ENSO is monitored in a number of ways. A simple but effective measure is the SOI. The SOI is calculated from the monthly or seasonal fluctuations in the pressure difference between Tahiti and Darwin. Sustained negative values of the SOI often indicate El Nino episodes, while positive values indicate La Nina episodes (Figure 1.12), also for more information see **http://www.bom.gov.au/climate/glossary/elnino.shtml.**

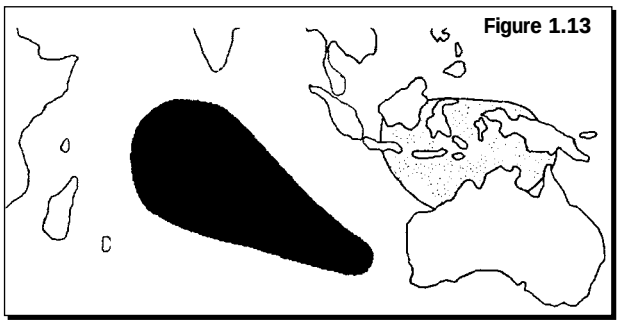
ENSO and South-west WA

Correlations of ENSO with rainfall in the wheatbelt are much less than those in the eastern states. In El Nino years there is a slight bias towards drier conditions at some stages of the year, while in La Nina years there is a slight bias to wetter conditions. It must be noted that the correlations between rainfall and ENSO vary depending on the way in which the signals are used. For example, sometimes the trend in SOI is more useful than the actual values of the SOI.

Indian Ocean Dipole

A dipole pattern of sea-surface temperatures (SST) in the Indian Ocean has been related to bands of cloud that sweep across the continent from north-west to south-east, known as north-west cloudbands. These cloudbands are important rainfall mechanisms form April to August through the Gascoyne, Murchison and northern agricultural areas in particular, and are often associated with the break of the season for the northern and central wheatbelt.

When there is warm water north of Australia and a relatively colder region in the central Indian Ocean west of the continent (see figure 1.13), the resulting stronger than normal sea surface temperature gradient assists in producing the moisture-laden north-westerly flow over Australia enhancing the occurrence of north-west cloud bands. The reverse pattern of relatively cold water in the central Indian Ocean is associated with reduced rainfall by suppressing north-west cloudbands. Research at CSIRO is investigating links with the SST anomalies and the depth of warm water near the surface, the sea level height, the transport of water around the Indian Ocean and also the links with ocean patterns in the Pacific.



Indian Ocean dipole.

The Antarctic Circumpolar Wave

This phenomenon has only recently been discovered and while its impact appears to be strongest in southern Australia, it is not yet known how significant it is for Western Australia. The southern ocean contains a large current which flows continuously around the Southern hemisphere at about 10cm per second, carrying most of the water with it. It takes about eight or nine years for this current to transport water completely around the globe.

Carried along with this current are two large regions of relatively warm water, thousands of kilometres across and 1km deep, alternating with two equally large regions of relatively cold water. This pattern is called the Antarctic Circumpolar Wave (Figure 1.13) and, like ENSO, appears to be due to interactions between the ocean and the atmosphere. The wave is also associated with pressure and wind patterns and the extent of sea-ice from Antarctica.

When the warm region is present south of Australia, winds carry slightly more moisture than usual causing winters to be slightly wetter and warmer than normal. Conversely, cold water south of Australia brings cooler and drier conditions to southern Australia. Being such a recent discovery it is difficult to assess the significance of this feature and how it affects rainfall in south-west Western Australia.

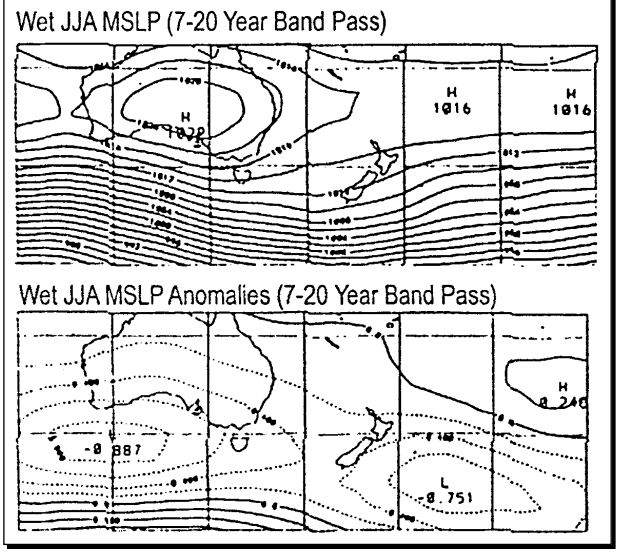
■ CLIMATE VARIABILITY AND SEASONAL FORECASTING

(continued)

Wet and dry years

A CSIRO study has compared pressure patterns between the wet and dry winters in Western Australia (Allan and Haylock, 1993). By compositing the pressure fields they produced pressure fields and anomaly fields for both the dry and wet years (see Figures 1.14a and 1.14b). This showed that in dry years, pressures were higher around Australia particularly to the immediate south of the continent. In the wet years, pressures were lower around Australia (particularly south of Western Australia) suggesting an increase in cold front activity.

Figure 1.14a



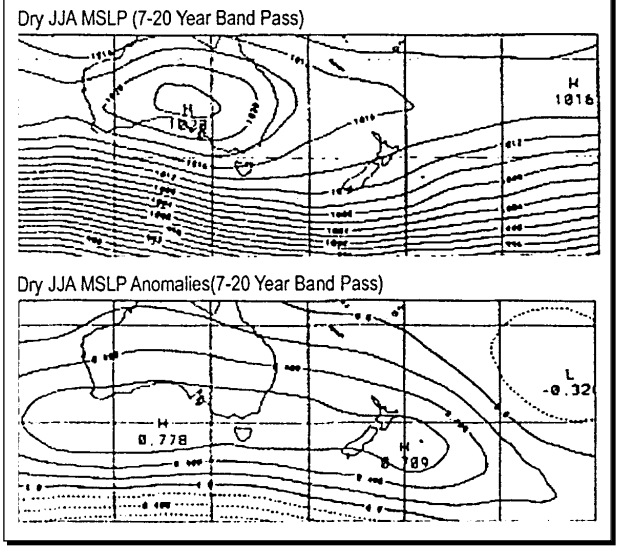
Explaining the variations – some examples

Let's return to the years 1992 (wet) and 1994 (dry). Although El Nino events tend to last for only 12 to 18 months there was an extended period of El Nino conditions between 1991 and 1994. However, there were noticeable differences between the two years in terms of global patterns.

By early 1992 an El Nino event had reached full maturity and it began to weaken in autumn. Nevertheless, the average SOI for January to April was –19.4, an exceptionally low value. This weakening coincided with a strong Indian Ocean dipole signal associated with considerable north-west cloudband activity. Well above average rainfall occurred in autumn and winter through much of southern Western Australia with some record totals in the eastern wheatbelt and Goldfields area.

In 1994, the SOI decreased from near zero values in January and February to be strongly negative for the remainder of the year signalling the re-emergence of El Nino. In addition, a reverse Indian Ocean dipole with relatively very cold water off Indonesia led to a suppression of north-west cloudbands. Conditions in the wheatbelt were very dry until the end of May and yearly totals were below average. While we do not fully understand the mechanisms that cause these seasonal rainfall variations, it is clear that the oceans have a major role to play.

Figure 1.14b



What does it mean for seasonal forecasts?

How these mechanisms relate to each other and the combined affects on our rainfall are the basis of research to improve seasonal forecasting. Until quite recently the Bureau of Meteorology's seasonal outlooks were based entirely on ENSO. A more sophisticated scheme using ocean patterns in both the Pacific and Indian Oceans is now operational. These are three-month outlooks giving the probability of receiving below average, average and above average rainfall. The accuracy varies during the year, and with each year, according to variations in the oceanic system. A summary of the outlook is available on the internet (http://www.bom.gov.au/climate/ahead/rain_ahead.shtml, by Weather by fax (1902 935 251) or through some media outlets.

The Indian Ocean Climate Initiative (IOCI) is a Western Australian initiated partnership to foster research into climate variability and development in seasonal forecasting. The results from this effort are likely to improve the understanding of seasonal mechanisms and hopefully lead to improved forecast skill on a seasonal basis.

■ CLIMATE VARIABILITY AND SEASONAL FORECASTING

(continued)

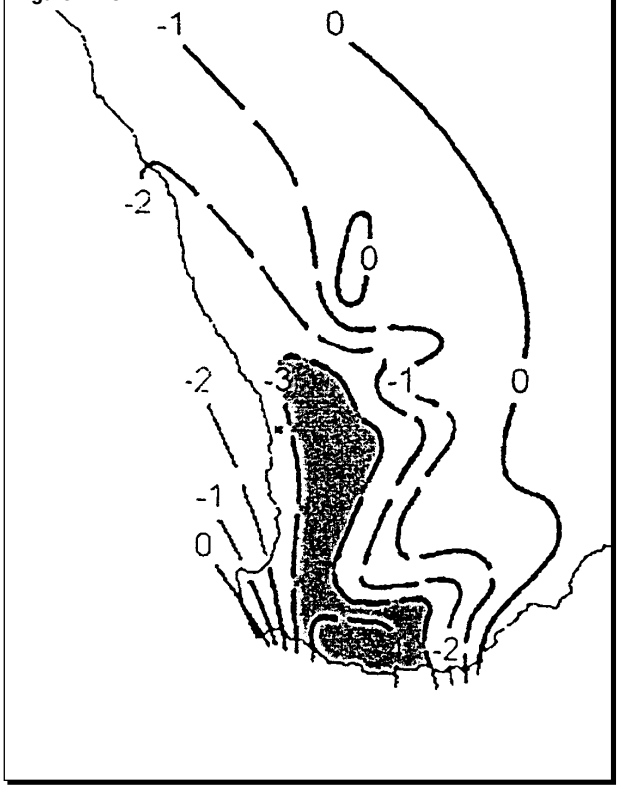
Climate trends in rainfall and temperature

Apart from year to year variability, the issue of long-term changes in rainfall and temperature patterns is of great importance, and concerns over global warming and its impacts have attracted great interest over the past decade or so.

Rainfall has declined in the south-west over the course of this century particularly in the far south-west since the 1940s (Figure 1.15). The trend in May to October rainfall closely matches the annual rainfall trend, although the November to April trend is weaker and more varied. Rainfall patterns in the eastern wheatbelt show less obvious trends.

Trying to understand the mechanisms of these changes and ultimately to be able to predict future rainfall are aims of a major research study. The current downward trend in winter rainfall over the south-west may be due to a general warming of a wide area of the Indian Ocean over the last few decades and variations in the large-scale atmospheric circulation across southern Australia since 1971. This trend may be regarded as a part of the natural variability of the climate system. This is supported by the fact that annual rainfall increased from the earliest rainfall records last century until the early to mid part of the 20th century.

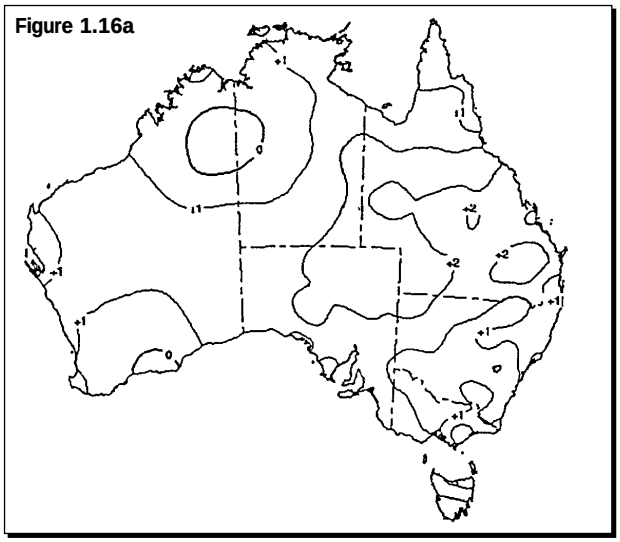
Figure 1.15



Trend in annual rainfall 1910-1989 (%/decade).

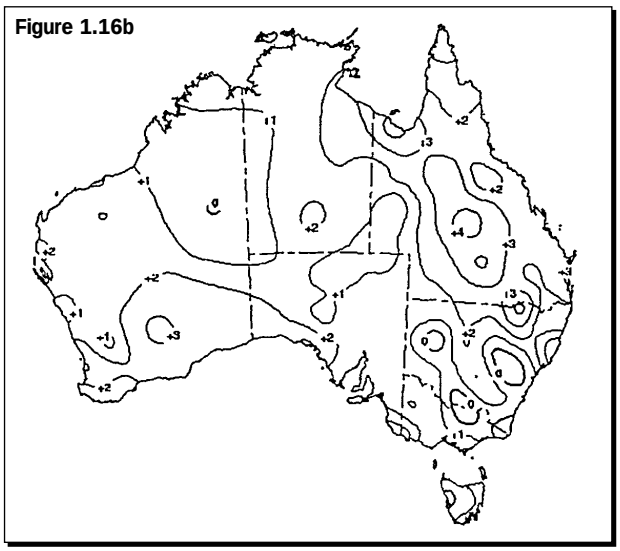
Consistent with trends elsewhere in Australia, average maximum and minimum temperatures have increased in Western Australia since instrumental records began (Figures 1.16a and 1.16b). There are many difficulties associated with comparing historical temperatures including change of instrument type, changes in observing practices and sites, and changes in the environment surrounding the instrument (particularly in urban areas). Nevertheless, with these issues taken into account research into observations of temperature indicate a definite long-term increase.

Figure 1.16a



Trend in annual maximum temperature (1959-94).

Figure 1.16b



Trend in annual minimum temperature (1950-94).

■ CALCULATING RAINFALL PROBABILITIES FROM DECILES

John Cramb
Western Australian Regional Office, Bureau of Meteorology

Deciles

Deciles are a method of describing rainfall probabilities for a month, group of months or a year. They are therefore useful for comparing recent rainfall with the average. Because rainfall and crop yield are closely related, they may therefore give some clue to likely yields at the end of season.

Deciles are obtained by dividing the historical rainfall into tenths. The deciles obtained range from 1 to 9 and each has a corresponding rainfall total expressed in millimetres. For example if a monthly total of 65mm has a decile rating of 3 – less than 65mm will be received in 3 years out of ten, and greater than 65mm in seven years out of ten.

Deciles can be summarized as follows:

- ***Decile 9*** 9 in 10 seasons receive less rainfall (or only one season in 10 receives more)
- ***Decile 8***
- ***Decile 7***
- ***Decile 6***
- ***Decile 5*** 5 in 10 seasons receive less than this amount and 5 in 10 more.
- ***Decile 4***
- ***Decile 3***
- ***Decile 2***
- ***Decile 1*** Only 1 in 10 seasons receives less than this amount, 9 in 10 seasons receive more.

Deciles are specific to the location where the rainfall was recorded. Decile values for monthly and annual rainfall totals have been calculated by the Bureau of Meteorology for many centres in Western Australia and are freely available. As an example, Table 1.2 gives the monthly and annual decile rainfalls for Merredin.

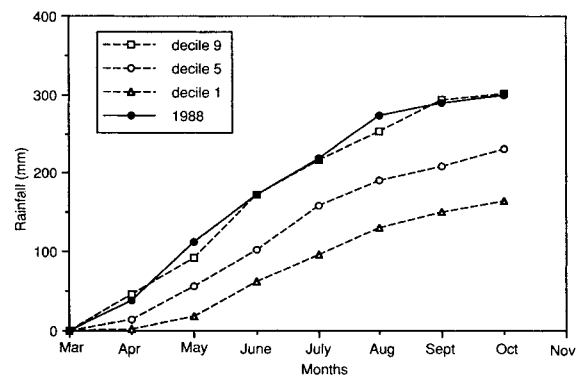
For the annual totals for Merredin, the values opposite decile 9 indicate that only one year in ten will have an annual rainfall greater than 410mm, whilst nine years in ten will have 216mm (decile 1). Note that decile 5 (301mm), the value for which half of all years will be above and half below, is very close to the long term average of 309mm.

The same can be done to the monthly rainfalls. For example, June rainfall will be less than 19mm in only one year in ten.

Using deciles to track seasonal conditions

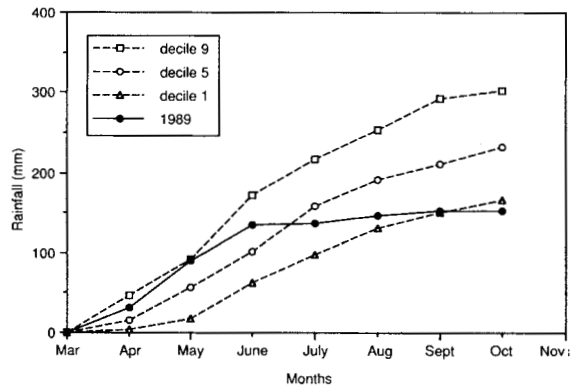
Deciles for the total rainfall received in two, three, or more consecutive months can be calculated and the growing season conditions can be tracked. Starting in April, compare the rainfall received for the month with the decile 9, decile 5 and decile 1 values. Then at the end of May, calculate the total rainfall received for April and May, and compare this with the decile values for the two months combined.

Figure 1.17a **Merredin 1988**



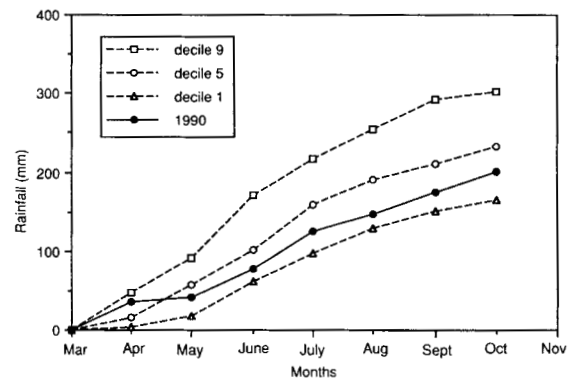
April to October rainfall and cumulative decile rainfall charts for Merredin for 1988

Figure 1.17b **Merredin 1989**



April to October rainfall and cumulative decile rainfall charts for Merredin for 1989.

Figure 1.17c **Merredin 1990**



April to October rainfall and cumulative decile rainfall charts for Merredin for 1990.

CALCULATING RAINFALL PROBABILITIES FROM DECILES

(continued)

In the same way at the end of June, compare the total rainfall for the three months with the appropriate deciles for the three month period; and so on to the end of the season.

The results of this analysis are most easily understood by drawing the cumulative rainfall at the end of each month on a graph with the decile values. Figure 1.17 shows the cumulative rainfall at Merredin in 1988 (a very good season), 1989 and 1990 from the end of April to the end of October. The decile 1, decile 5 and decile 9 rainfall values are also shown.

For 1989, the season was well above average at the end of May and June, but then deteriorated to have below average seasonal rainfall to the end of October. For 1990, seasonal conditions were below average.

Deciles can also be used to update the probabilities for total seasonal rainfall, and since this is closely related to grain yield, give some clue to the yield prospects for the season.

If the season is going to be good, with above average rainfall, there are likely to be good responses to additional nitrogenous fertilizer, copper or molybdenum sprays may be required on high biomass crops and there are likely to be good yield responses to herbicides.

On the other hand, if the season is going to be below average, the chance of profitable responses to additional inputs is less or may even be negative.

Making such forecasts, which look ahead to the end of the season, is more complex than simply tracking the progress of the season, but such services are potentially of great value.

■ LANDFORMS AND SOILS OF SOUTH-WESTERN AUSTRALIA

Peter Tille
Agriculture Western Australian Soils Group

General soil characteristics

The soils of south-western Australia have a reputation for being sandy with inherent low fertility. Many major and minor elements such as N, P, K, S, Cu, Zn, Mn and Mo are deficient for plant growth. This is largely due to the age of the soils and their high degree of weathering, there being a small proportion of freshly renewed soils in comparison with most other wheat growing regions of the world. The weathering has also led to a predominance of sandy textured topsoils consisting of highly resistant quartz grains. Silty materials are rare and the clayey subsoils are dominated by kaolinitic minerals. The widespread occurrence of iron and aluminium rich laterite is another characteristic of the soils and landscape. While the above generalisations are broadly true, there are wide variations in soil types and fertility.

History and geology

The distinctive landforms of south-western Australia and the soils associated with them reflect their geological history. Much of the south-west occurs on a geologically stable area, known as the Yilgarn Craton, which consists of acid granitic rocks and is one of the oldest remaining portions of the earth's surface (over 2,500 million years old). The western boundary of the Yilgarn Craton is the Darling Fault which extends from Mullewa and Three Springs to Donnybrook and Nannup. This fault is one of the largest lineaments on the Earth's surface being 1,000 km long with a current topographical expression of up to 200 m along the Darling Scarp.

Granitic geology occurs along the south coast and at Margaret River and Northampton. While these rocks are younger the those of the Yilgarn Craton, they are still over 1,000 million years old. All of these areas have been worn down by erosion for several hundred million years. As a result of the old age of the landscape there are no major mountain ranges, relief is low and subdued, and drainage often sluggish.

To the west of the Darling Scarp, the underlying geology consists mainly of sedimentary rocks, such as sandstones and siltstones. Along the coast between Geraldton and Busselton these are overlain by the more recent sediments of the Swan Coastal Plain. Sedimentary rocks are also found along the South Coast overlying the granitic basement. In some places the sedimentary rocks have given rise to prominent landscape features such as the flat topped mesa of the Moresby Range near Geraldton. The Stirling and Barren Ranges on the South Coast have formed on metamorphosed sediments.

Much of the south-west is overlain by a mantle of deeply weathered material dating back 50 million years or more. This weathered surface is commonly 30-50 m deep, laterite is a prominent feature which has formed over granitic and sedimentary rocks. The lateritic profile is characterised by an accumulation of iron and aluminium near the surface. It typically consists of a surface layer of sand and ironstone gravel overlying an iron indurated crust of cemented gravel (duricrust). The duricrust is typically underlain by a heavily mottled clay (mottled zone) grading into a pale coloured clay from which most of the iron has been removed (pallid zone). Below this is a partially weathered material (saprolite) which typically consists of a gritty material retaining the fabric of the underlying rock.

The extent of dissection is controlled by earth movements mainly around the south-western margin of the otherwise stable Yilgarn Block. Upwarping to form the Darling Range, and a downward sag along the zone of seismic activity running through Brookton, Beverley, Northam and beyond has led to renewed down-cutting by the marginal rivers and streams.

The process has extended inland to truncate the ancient drainage lines represented by the salt lake chains to a limit shown on Figure 1.18 as the Meckering Line. Some geologists believe that the salt lake chains of the interior represent ancient river systems which flowed before the super-continent of Gondwanaland began to break up and the major land masses of the world drifted apart.

Upstream of the Meckering Line lies the Zone of Ancient Drainage where lateritic profiles are widespread on the extensive uplands between the wide, flat floored trunk valleys with low gradients.

Downstream is the Zone of Rejuvenated Drainage with more frequent dissection, closer more incised stream system, and the divides are smaller. They are again crowned with laterite and often defined by prominent breakaways. However, the pallid zone clays are still present on the relatively steep valley side slopes beneath a generally shallow sandy veneer.

In the higher rainfall areas lateritic profile is absent only where slopes are steeper and topographic relief greater. Erosional and depositional processes acting over a very long time have dissected the lateritic landscape to expose limited areas of fresh rock on which younger and more fertile soils have formed. In the Darling Range, despite its well developed stream system, and generally hilly topography, lateritic materials mantle almost the whole landscape, often in the form of duricrust. Perhaps due to the high rainfall, weathering is even more extreme, so that oxides of aluminium are concentrated in relation to other constituents to form bauxitic laterites in parts of the landscape.

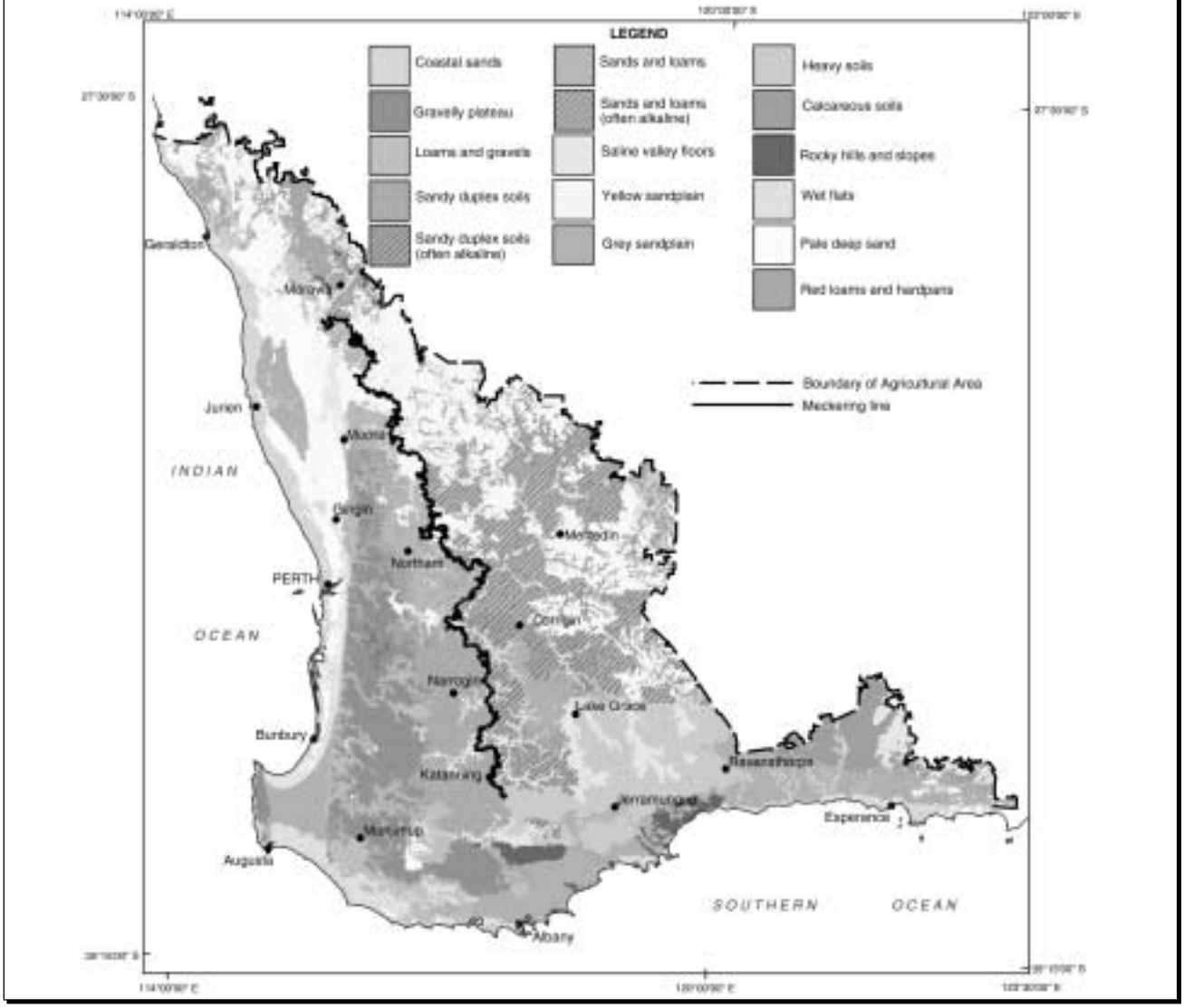
Salt in the landscape

The deeply weathered profile in south-western Australia contains large quantities of soluble salts, mainly sodium chloride. In the wheat growing areas the salt stored

■ LANDFORMS AND SOILS OF SOUTH-WESTERN AUSTRALIA

(continued)

Figure 1.18



The soils of south-western Australia.

in the landscape may amount to a million or more kilograms per hectare, most of it in the deep subsoils and saline watertables.

The salts originate in the ocean, and are carried inland in dilute concentration in the rainfall. While the water is lost from the soils by evaporation and transpiration, there is no escape for the salts, which are retained. Even the large amounts present would have taken only about 10,000 years to accumulate at present rates of accession, a very short time in comparison with the long period of leaching which must have preceded it.

Soils of the wheat growing areas

The major soil types of Western Australia have been placed into 56 groups. These groups have been further amalgamated into 12 supergroups. The supergroups are defined using three primary criteria:

- the texture profile
- the presence and nature of coarse fragments
- the water regime

The soil groups are further divided by the following secondary and tertiary criteria:

- the presence of carbonates
- topsoil colour
- horizon or profile depth
- pH (acidity or alkalinity)
- soil stricture

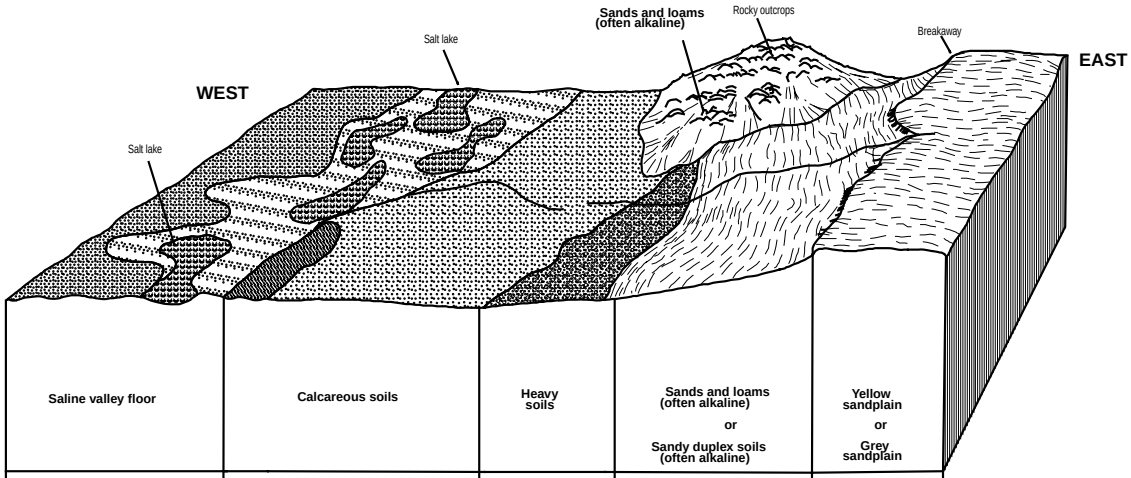
Figure 1.18 shows the distribution of these soils. This mapping is based on the detailed (mapping scales ranging from 1:50,000 to 1:250,000) soil-landscape mapping of the agricultural area of Western Australia. Contact the Natural Resources Assessment Group of Agriculture Western Australia for more details.

The soil types and associated natural vegetation of the wheat growing areas are shown in Figures 1.19 and 1.20.

LANDFORMS AND SOILS OF SOUTH-WESTERN AUSTRALIA

(continued)

Figure 1.19



	Saline valley floor	Calcareous soils	Heavy soils	Sands and loams (often alkaline) or Sandy duplex soils (often alkaline)	Yellow sandplain or Grey sandplain
SOIL-LANDSCAPE GROUPING					
MAJOR SOIL GROUPS	Alkaline grey deep sandy duplex, Alkaline grey shallow sandy duplex, Calcareous loamy earths, Saline wet soils, Salt lake soils, Loamy duplex soils	Calcareous loamy earths, Alkaline grey shallow loamy duplex, Alkaline grey shallow sandy duplex, Alkaline red shallow loamy duplex	Grey shallow sandy duplex (often alkaline), Grey shallow loam duplex (often alkaline), Grey non-cracking clay, Heavy cracking clay	Grey deep sandy duplex (often alkaline), Grey shallow sandy duplex (often alkaline), Loamy earths, Sandy earths. Grey deep sandy duplex (often alkaline), Grey shallow sandy duplex (often alkaline), Duplex sandy gravels, shallow gravels	Yellow sandy earths, Acid yellow sandy earths, Yellow deep sands, Gravels. Gravelly pale dep sands, Grey deep sandy duplex, Pale deep sands, Duplex sandy gravels
VEGETATION	Salmon Gum, Gimlet, Morrel, Bluebush, Saltbush, Melalueca, Samphire, Barley Grass, Bare ground	Morrel, Salmon Gum, York Gum, Wandoo, Gimlet	Mallee Species, Moort, Yate, Salmon Gum	Salmon Gum, Wandoo, Mallee, Gimlet. Wandoo, Salmon Gum, York Gum, Jam, Sheoak	Banksia, Sandplain pear, Tammar, Wodjil, Sanplain Mallee, Christmas Tree, Flame Grevillia

Adapted from: Lantzke and Fulton "Land Resources of the Northam Region" Land Resources Series No. 11, Agriculture Western Australia

Soil types of the eastern wheatbelt and their associated vegetation.

Detailed descriptions of selected soil types are given in the Appendices.

Figure 1.19 represents a cross section of a typical wheatbelt valley inland of the Meckering Line. Modification of the old landscape by natural erosion and deposition is relatively minor, but nevertheless has had an important impact on the soil pattern.

The lateritic profile is best preserved on the upland, but sands tend to accumulate in the depressions as yellow sandy earths, leaving ironstone gravelly soils on the higher areas.

On steeper valley side slopes stripping may expose mottled or pallid zones clays upslope with accumulations of sand downslope to give extensive areas of sandy duplex soils and loamy duplex soils with yellow or pale subsoils.

Where fresh bedrock outcrops or is close to the surface it provides a source of relatively unweathered material which gives rise to naturally more fertile soils, often red loamy earths. These soils may be developed from the bedrock in situ or on extensive water laid deposits derived from it to form the 'heavy land' of the broad wheatbelt valleys.

Figure 1.19 shows the typical situation in which the deeply weathered pallid zones lie beneath the valley floor, carrying saline water tables where the salt concentration my be several times that of sea water.

The salt lakes, when dry, are the source of wind blown deposits lying generally along the south-eastern lake shores. Near the lakes they are in dune-like form, often rich in gypsum, sometimes suitable for commercial exploitation. Further out, layers of silty, calcareous and saline loams give rise to the calcareous loamy earths (the so-called 'snuffy morrell' soils).

Figure 1.20 shows a valley cross section downstream of the Meckering Line. The soil pattern is essentially the same, but slopes are steeper, valleys more sharply incised, and salt lakes absent. Upland areas with sand thins out and the clays approach the surface soaks or swamps with fresh or brackish water appear, often developing after clearing upslope.

Soils and cereal growing

Cereal growing in south-western Australia presents a variety of management problems arising directly from the inherent properties of the soils.

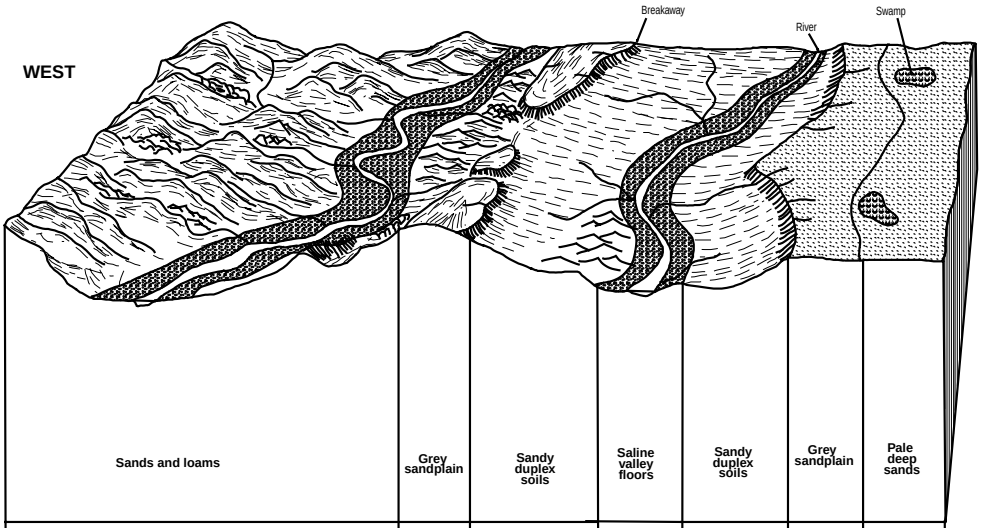
The sandy surface soils are extremely deficient in major and minor nutrient elements. The low clay content means they have a low capacity for retention of most applied nutrients, while the presence of iron oxides leads to fixation and unavailability of applied phosphate.

Resistance to chemical change, known as buffering capacity, is low, so that acidity of surface soils is readily induced by fertilisation.

■ LANDFORMS AND SOILS OF SOUTH-WESTERN AUSTRALIA

(continued)

Figure 1.20



SOIL-LANDSCAPE GROUPING	**Sands and loams**	**Grey sandplain**	**Sandy duplex soils**	**Saline valley floors**	**Sandy duplex soils**	**Grey sandplain**	**Pale deep sands**
MAJOR SOIL GROUPS	Grey deep sandy duplex, Red deep sandy duplex, Grey shallow sandy duplex, Red shallow sandy duplex, Red deep loamy duplex, Red loamy earth	Gravelly pale deep sands, Grey deep sandy duplex, Pale deep sands, Duplex sandy gravels	Grey deep sandy duplex, Grey shallow sandy duplex, Duplex sandy gravels, Deep sandy gravels	Grey deep sandy duplex (often alkaline), Grey shallow sandy duplex (often alkaline), Saline wet soils, Loamy duplex soils	Grey deep sandy duplex, Grey shallow sandy duplex, Duplex sandy gravels, Deep sandy gravels	Gravelly pale deep sands, Grey deep sandy duplex, Pale deep sands, Duplex sandy gravels	Pale deep sands, Gravelly pale deep sands, Grey deep sandy duplex, Duplex sandy gravels, Wet soils
VEGETATION	York Gum, Jam, Sheoak, Salmon Gum, Wandoo, Flooded Gum	Sandplain Pear, Banksia, Tammar, Ti-tree, Christmas Tree, Wandoo	Wandoo, Mallet, Jam, Tammar, Salmon Gum, Sheoak	Wandoo, York Gum, Jam, Salmon Gum, Sheoak	Wandoo, Mallet, Jam, Tammar, Salmon Gum, Sheoak	Sandplain Pear, Banksia, Tammar, Ti-tree, Christmas Tree, Wandoo	Banksia, Christmas Tree, Wandoo, Blackboy, Ti-tree, Rushes

Adapted from: Lantzke and Fulton "Land Resources of the Northam Region" Land Resources Series No. 11, Agriculture Western Australia

Soil types and associated vegetation west of the Meckering Line.

Some deep sands and sandy earths, particularly the acid yellow sandy earths, have naturally acid subsoils which tend to restrict root development.

The water holding capacity of sandy soils is low, so that although the soil water is readily available to plants, it can readily escape below the root zone, contributing to salinisation problems downslope.

Soil organic matter is low and readily lost under warm conditions, leading to poor soil structure and risk of wind erosion.

Kaolinitic clays and oxides of iron and aluminium, common in lateritic materials, have a relatively low capacity to adsorb and retain nutrients, so that the more soluble nutrients such as nitrogen, sulphur and potassium can leach readily.

The tendency of the clays to disperse in water is accentuated by the presence of the sodium ion, leading to structural deterioration, increased run-off and waterlogging downslope.

Management for sustainable production will therefore always be difficult because of the particular characteristics of the soil resource. Advances are likely to come from progressive adaptation of farming systems to soil and climatic conditions.

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CHAPTER TWO

THE STRUCTURE AND DEVELOPMENT OF THE CEREAL PLANT

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■ THE STRUCTURE AND DEVELOPMENT OF THE CEREAL PLANT

Tim Setter and Peter Carlton

The structure of the wheat plant described in this chapter is the starting point to understanding the growth and development of the crop, its nutrition and the reasons for particular management practices.

Like all of the temperate cereals, wheat undergoes profound changes in structure through its life cycle. The delicate growing point at the shoot apex, at first produces leaves, and then later changes to form the flowering spike or ear. The stem, at first compact and measuring a few millimetres, rapidly expands to a structure that may be a thousand millimetres or longer.

Plant growth and development concerns the length of the plant's life cycle, its subdivision into distinct stages, and the processes of formation of the plant's organs – the leaves, tillers and spikelets. How a wheat plant develops these organs is important because it is the basis for the adaptation of cultivars to environments – it is the reason why European cultivars are largely unsuited to Western Australia, and why cultivars with differing developmental patterns are needed for different sowing dates and regions.

Structural and developmental patterns are also important because many decisions about nutrition and crop management are best made on a developmental rather than a calendar time scale.

The major developmental processes for a cereal are:

- germination and seedling establishment
- initiation and growth of leaves
- tillering
- growth of the root system
- ear formation and growth
- stem extension
- flowering and grain growth.

The developmental processes overlap and are closely linked so that the form and structure of the plant evolves as the integration of many consecutive and interacting processes.

■ DESCRIPTION OF THE WHEAT PLANT

The temperate cereals are all annual grasses. They have evolved as humanity's constant companions for about 11,000 years commencing in the Middle East. This evolution to the modern high yielding cereals, from their lower yielding wild ancestors, was critical to the development of modern society. The cereals group includes wheat *(Triticum)*, barley *(Hordeum)*, Oats *(Avena)*, rye *(Secale)* and the man-made hybrid triticale *(Triticosecale)*.

There are about 30 species of wheat, and more than 40,000 cultivars have been produced in the world. Wheat species can be divided into three groups depending on the number of chromosomes present in vegetative wheat plant cells: diploid (14 chromosomes); tetraploid (28 chromosomes); and hexaploid or bread wheats (42 chromosomes). These species can cross breed in nature or by plant breeders.

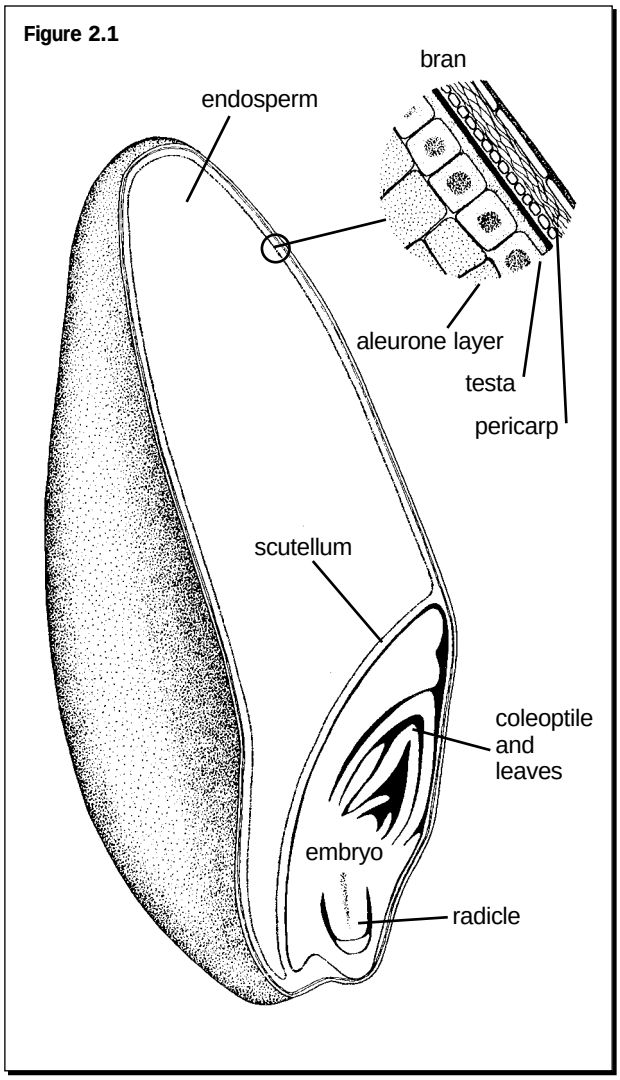
Only three species of wheat are commercially important:

Triticum aestivum – bread wheats or common wheats. These hexaploid wheats are the most widely grown in the world.

Triticum turgidum cv. *durum* – durum wheats. These tetraploid wheats are hard wheats (from Latin, *durum*, meaning 'hard'), e.g. cv. Yallaroi and Wollaroi. Flour from these wheats holds together well due to high gluten content, so cultivars are usually used for pasta and bread products.

Triticum compactum – club wheats. These hexaploid wheats are identified by their compact, club-shaped head, e.g. cv. Tincurrin. This species is sometimes considered a subspecies of common wheat. These are usually soft grained wheats often used for cake flour.

Wheat and all other grasses have a common structure which provides the basis for understanding the growth and development of the crop and the reasons for particular management practices.



Structure of the wheat grain.

The grain

The *grain* is the unit of reproduction in cereals as well as the economic product. Grain is the small (3-8 mm long), dry, seed-like "fruit" of a grass, especially a cereal plant. (Note: *kernel* is an older term for the edible seed of a nut or fruit, e.g. as in a kernel of corn).

Grain is considered as a one-seeded "fruit" (called a *caryopsis*) rather than a "seed" according to botanical definition (see Glossary at the end of this Section). A *seed* is a mature *ovule* which consists of an embryo, endosperm and the seed coat. However, a *fruit* is a mature *ovary* which includes the ovule or seed, in addition to the ovary wall that surrounds the seed *(pericarp)*.

In wheat, the pericarp is thin and fused with the seed coat (Figure 2.1 insert), and this makes wheat grain a true "fruit". In other plants the pericarp may be fleshy as in berries, or hard and dry forming the pod casing of legumes. Crops with true "seeds" as the dispersal unit include lupins and canola.

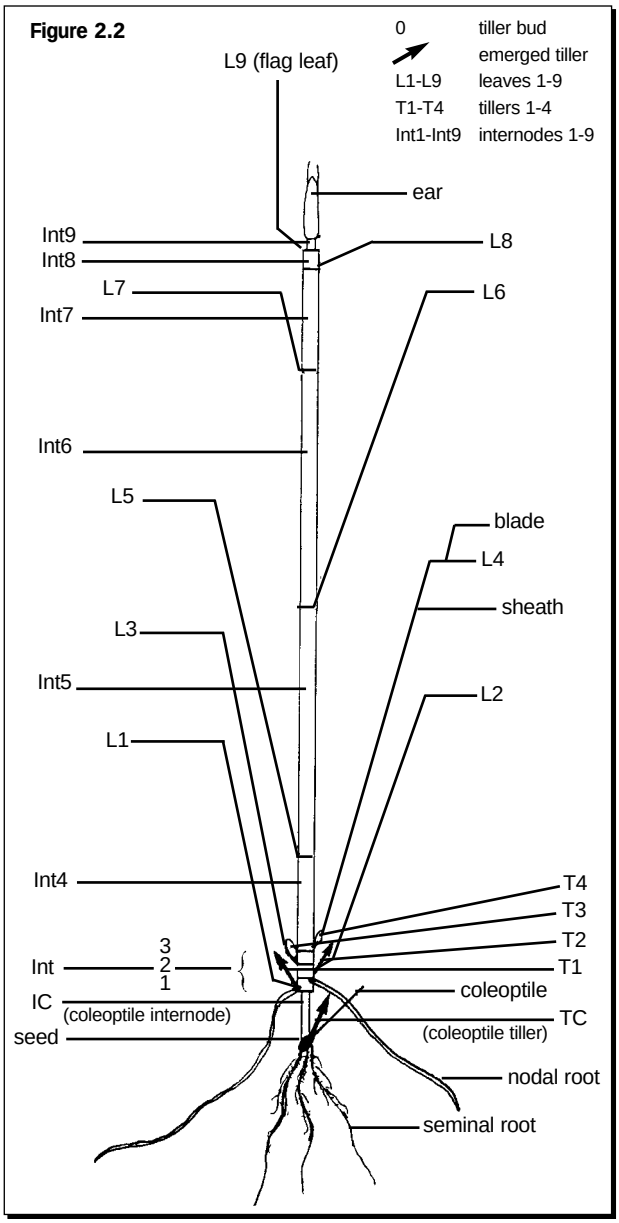
Seen in cross-section (Figure 2.1), the main constituents of grain are the *bran* coat, the *embryo* or young plant, and the *endosperm*. In most wheat cultivars, the proportions of grain are: bran 14%, endosperm 83% and embryo 3%.

The bran coat covering the grain is made up of an outer *pericarp* derived from the parent plant ovary wall; a *testa* or seed coat derived from the *ovule*; and the *aleurone layer*, important as a source of enzymes and growth factors in germination (Figure 2.1).

The endosperm makes up the bulk of the grain, it is the energy for the germinating seed, and it is the store of starch and protein which is milled for production of white flour. In comparison, whole wheat flour is made up of the ground products of the entire grain and therefore naturally contains more vitamins and minerals from the bran and embryo.

The embryo (Figure 2.1) consists of a short axis with a terminal growing point or shoot apex, and a single primary root known as the *radicle*. Around the growing point are the *primordia* of the first three leaves.

■ DESCRIPTION OF THE WHEAT PLANT *(continued)*



Schematic diagram of a mature wheat plant highlighting tiller, leaf and internode numbering and position (redrawn from Kirby and Appleyard, 1987).

The shoot is enclosed in a modified leaf called the *coleoptile* which serves as a protective sheath as the shoot emerges through the soil. When wheat is sown, the maximum coleoptile length ranges from less than 60 mm to more than 90 mm in different cultivars. This difference will affect the maximum sowing depth and potential for emergence of crops (see Chapter 7).

Below the shoot apex, but above the point of attachment of the coleoptile, is the section of stem which will elongate to form the *sub-crown internode*. This tissue elongates during seed establishment so that the base of the stem (crown) forms close to the soil surface.

Between the embryo and the food reserves stored in the endosperm is the *scutellum* (from Latin meaning 'shield'), a broad, elliptical structure which acts as the transfer route for substances moving from the endosperm to the growing embryo (Figure 2.1).

Both the scutellum and the coleoptile are tissues that have been modified from the single cotyledon in cereals (monocots), and distinguish them from the double cotyledons that occur in crops like lupins and peas (dicots).

The leaf

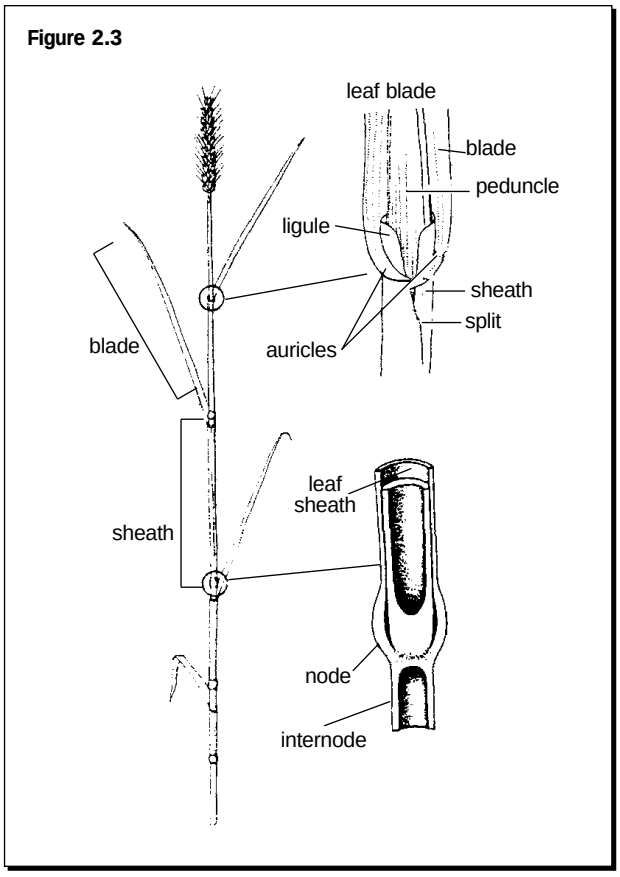
About three leaves are present as minute primordia around the shoot apex of the embryo at germination. After germination, more leaves are produced sequentially on alternate sides of the apex.

The odd-numbered leaves will be one side of the main stem and one above the other, while the even numbered leaves will be on the opposite side of the stem. The final leaf to develop before ear emergence is the *flag leaf* (Figure 2.2).

The coleoptile is numbered as zero and appears on the 'even' side of the plant (Figure 2.2).

The wheat leaf is long and narrow with two distinct parts: the basal *sheath* which encircles the stem of the plant and contributes to stem strength, and the leaf *blade* which is the primary photosynthetic tissue of the plant (Figure 2.3).

The sheath and the blade grow from separate *meristems*



Detailed structure of the stem and leaf of the wheat plant.

■ DESCRIPTION OF THE WHEAT PLANT *(continued)*

at their bases, so the oldest parts of a leaf are the tip of the blade and the top of the sheath. Where the blade and sheath join, there are structures called the *ligule* and the *auricles* (Figure 2.3).

Tillers

Tillers are basal branches which arise from buds in the axils of the leaves on the mainstem. Structurally, they are almost identical to the mainstem, and are thus potentially able to produce an ear. Leaves on a tiller are also produced alternately, but they are at 90° to the orientation of leaves on the mainstem.

The tiller is initially enclosed in a modified leaf – the *prophyll* – which is similar to the coleoptile that encloses the mainstem during emergence.

A tiller is designated by the number of the leaf axis that it occurs in. Hence, the tiller in the axis of Leaf 1 to the mainstem is referred to as Tiller 1 (Figure 2.2).

Tillers produced from leaves on the main stem are called *primary tillers*; these in turn can form their own tillers, called sub-tillers or *secondary tillers*. Sometimes a tiller originates in the axis of the coleoptile and this is called the *coleoptile tiller* (Figure 2.2). In long season winter wheats it is possible for sub-sub-tillers, or tertiary tillers to be produced, although this is unusual.

Reduced tillering in new cereal cultivars is proposed by some scientists to try and increase yield, i.e. by eliminating stems that do not produce ears. However, tillers that have their own roots often produce ears.

Tillers may also contribute to grain yield as a source or sink for excess sugars and nutrients of the mainstem. In locations where insects, diseases or environmental stresses are common, tillers offer assurance that crop losses are minimal. The diversity of locations wheat is grown in will assure a diversity of cereal plant types for these environments.

Characteristics of the shoot plant structures described above are representative for a species, and can be used to identify crops and weeds, e.g. to distinguish between wheat and wild oats (Table 2.1).

The roots

Cereals possess two distinct root systems (Figure 2.2):

- *Seminal roots* which develop from primordia within the grain. The word seminal comes from Latin *seminalis*, meaning 'belonging to seed'.
- The crown, adventitious or *nodal roots* which subsequently develop from the nodes within the crown.

As is the case for leaves and tillers, all the root axes of a plant can be given designations to describe their position, type and time of appearance on the plant.

The growing, meristematic tissues of roots are located in the first 2-10 millimetres of the tip of each root. Hence, as roots grow the meristematic tips move further away from the shoot deep into the soil. This contrasts with the structures of blades and sheaths where the meristematic tissue remains close to the stem and pushes older tissues away from the plant.

Why roots have evolved differently from leaves to have their growing meristematic tissue at the tip is unknown. One possibility is that this allows immediate control over root growth in the event of environmental changes such as water or nutrient supply. Hence this enables better control of the direction of root growth in the diverse soil matrix. (The analogy is therefore similar to the justification for placing a prime mover at the leading front, rather than at the back, of a series of trailers.)

The stem

The stem of the wheat plant is made up of successive *nodes*, or joints, and usually hollow *internodes* (Figs. 2.2

Table 2.1 – Shoot structures to identify cereals and selected weeds (see Figure 2.3)

Grass	Ligule	Auricles	Leaves	Leaf sheath
Wheat	fringed membrane	yes – large clasping, with hairs	*usually* twist clockwise; no hairs	split
Barley	membrane	yes – very large, without hairs	twist clockwise; usually hairless	split
Oats	membrane	none	twist anticlockwise; no hairs	split
Annual Ryegrass	membrane (<2 mm)	yes – large, clasping	no hairs	slight split
Barley grass	membrane (<2 mm)	yes – large, pointed	soft hairs	slight split
Wild oats	membrane (<2 mm); hairless	none	twist anti-clockwise; no hairs	split

■ DESCRIPTION OF THE WHEAT PLANT *(continued)*

and 2.3). The stem is wrapped in the sheaths of the surrounding leaves. This structure of stem and sheaths gives strength to the shoot, and it is what keeps the cereal shoot erect and reduces lodging.

Nodes are the places on stems where other structures such as leaves, roots, tillers and spikelets join the stem. This is also where the vascular channels carrying nutrients into and out of these organs join the vascular connections of the stem. Tissue between two adjacent nodes is known as the internode.

While the plant is young, the nodes remain packed close together and the leaves appear to originate from a single point – the crown of the plant. In fact, the *crown* consists of 8-14 nodes stacked closely above one another separated by internodes less than a millimetre in length.

Only when stem elongation begins, do the internodes begin to grow to form the characteristic tall jointed stem of the mature wheat plant (Figure 2.2).

As the stem grows, it evolves from a support tissue for leaves, to also become a storage tissue for carbohydrates and nutrients in preparation for subsequent grain filling. At the time of ear emergence, carbohydrates account for 25 to 40% of the dry weight of stems of most wheat cultivars grown in Western Australia. This is an adaptive trait for wheat grown in rainfed environments, since even if severe drought occurs at the end of the season this carbohydrate can be used to fill some grains.

The ear

The inflorescence or ear of wheat is a compound *spike* made up of two rows of *spikelets* (Figure 2.4) arranged on opposite sides of the central *rachis*. Like the stem, the rachis consists of nodes separated by short internodes, and a spikelet is attached to the rachis by the *rachilla* at each node. On each ear there is a single terminal spikelet arranged at right angles to the rest of the spikelets (Figure 2.4).

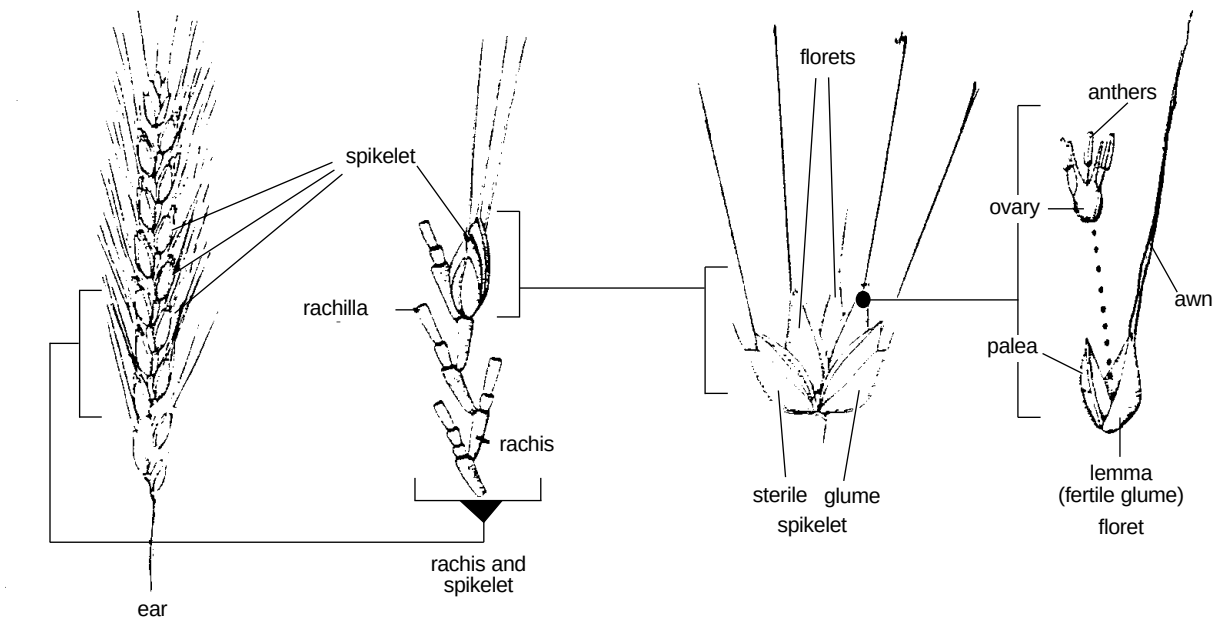
At the base of each spikelet are two chaffy bracts called sterile or empty *glumes* (Figure 2.4). These enclose up to ten individual flowers called *florets* in grasses, although the upper florets are usually poorly developed. Generally only 2 to 4 florets form grains in every spikelet. A typical wheat ear will develop 30 to 50 grains.

Each flower will produce one grain which grows in the axil of a bract called the *lemma*, and is enclosed by another bract called the *palea*. The long *awns* (sometimes called "beards") found on many modern wheats are extensions of the tip of the lemma (Figure 2.4).

The floret

Each floret or individual flower (Figure 2.4) is enclosed within a lemma and a palea. Within these enclosing structures there is a *carpel* which consists of the *ovary* with the feathery *stigmas*, and three *stamens* bearing the pollen sacs or *anthers*. These are the female and male reproductive tissues of the wheat flower. The ovary contains a single *ovule* which, when fertilised, forms the grain.

Figure 2.4



Structures of the wheat inflorescence (spike or ear), spikelet and floret of the wheat plant.

GLOSSARY

Aleurone layer. A layer of high protein cells surrounding the storage cells of the endosperm. Its function is to secrete hydrolytic enzymes to digest food reserves in the endosperm.

Auricle. A lobe at the base of a leaf; from the Latin *auris* meaning "ear" (hence a lobe).

Anther. A saclike structure of the male part of a flower in which the pollen is formed.

Anthesis. Flowering. Usually taken to mean the time at which pollen is shed.

Awns. A slender, often long, appendage extending from the tip of the lemma; occasionally referred to as the "beards" of wheat and barley.

Axil. The space between a leaf (or tiller) and the stem it is attached to. A tiller originates as a bud in the axil of a leaf.

Carpel. The female reproductive organ which in wheat consists of an ovary and two feathery stigmas. The ovary contains a single ovule.

Coleoptile. A sheath which protects the first leaf and shoot apex as they emerge to the surface during germination.

Floret. An individual flower of a cereal. Each floret has three anthers containing pollen and an ovary which, when fertilised may form a grain. Up to ten florets may form in each spikelet, but generally only 2-4 form grains.

Fruit. A mature ovary which includes the ovule (seed), in addition to the ovary wall (pericarp) that surrounds the seed.

Glumes. The outer chaffy bracts that enclose the wheat spikelet.

Internode. The stem tissue between any two nodes. In cereals, the elongation of these tissues is responsible for stem elongation and ear excertion.

Lemma. One of the thin bracts of a grass floret enclosing the caryopsis that is located on the side nearest the embryo and opposite the rachilla (see also palea)

Ligule. A membranous or hairy lobe on the inner surface of a leaf marking the join between the leaf blade and sheath.

Meristem. The localised region of active cell division, usually 2-10 millimetres long in cereal tissues. Meristems include those of the shoot and root (apical meristems), the bases of internodes (intercalary meristems), and the tiller buds (axillary meristems).

Node. The part of the stem from which a leaf or root may arise

Nodal roots. Also known as crown, coronal, or adventitious roots. Nodal roots are formed in association with the growth of leaves and tillers (see seminal roots)

Ovary. The part of the female part of the flower containing the ovule.

Ovule. The structure within the ovary of the flower that becomes the seed following fertilisation and development.

Palea. One of the thin bracts of a grass floret enclosing the caryopsis that is located on the side opposite the embryo

Pericarp. The ovary wall. It may be thin and fused with the seedcoat as in wheat, fleshy as in berries, or hard and dry as in pods of lupins.

Primary tiller. Tillers produced from leaf axis on the mainstem.

Primordium(-a). Organs in their earliest stage of development; as a leaf primordium.

Prophyll. A modified leaf that initially encloses the tiller; this tissue is similar to the coleoptile function in protecting the shoot during emergence.

Rachis. The main axis of a grass flower; in wheat, providing the attachment of many spikelets to the peduncle.

Rachilla. The secondary axis of a grass flower; in wheat, providing the attachment of a single spikelet to the rachis.

Radicle. The rudimentary root of a seed or seedling that forms the primary root of the young plant.

Scutellum. A flat, plate-like structure between the embryo and the endosperm of the grain. It is often viewed as a highly modified cotyledon in monocotyledons. It releases hormones which initiate germination and is the pathway for nutrients fed from the endosperm to the growing seedling.

Secondary tillers. Tillers produced from tiller axis with the mainstem.

Seed. A mature ovule consisting of the embryo, endosperm and seed coat (testa).

Sheath. The enclosing structure of the base of the leaf around the stem; in cereals, the leaf tissue connecting the blade to the stem node.

Shoot apex. The active growing point of a shoot. Consists of a dome of actively dividing cells which form the new structures such as leaves and spikelets

Seminal roots. The roots that arise from the seed; from the Latin *seminalis*, "belonging to the seed" (cf. nodal roots).

Spike. A basic type of inflorescence in which the flowers arise along a rachis and are essentially sessile (stalkless).

Spikelet. The structural unit of a grass flower that includes two basal glumes including one to several florets.

Stamen. The organ of the flower producing pollen. It consists of a filament bearing a terminal anther which contains the pollen grains

Stigma. The part of the carpel receptive to pollen.

Style. The stalk between the stigma and the ovary.

Sub-crown internode. The internode between the seminal roots and the crown of the plant. It elongates during seedling establishment to ensure that the crown is formed close to, but below the soil surface.

Testa. The outer covering of the seed; the seedcoat.

■ GROWTH SCALES FOR IDENTIFYING PLANT DEVELOPMENT

Growth scales are means of quantifying the growth stage of a crop in a standardised way and are useful when:

- There is a need to identify a particular growth stage for the safe application of a herbicide or fungicide. An example is the use of phenoxy herbicides where application too early or too late may damage the crop.
- Communicating the growth stage of a crop to advisers or research services when seeking advice on the development of diseases or nutrient deficiencies.
- Sampling plant tissues for nutrient analysis.

The Decimal code or Zadok's growth scale is a 0-99 scale of development that is recognised internationally for research, advisory work and farm practice. It is now used throughout Australia, particularly for application of chemicals or fertilizers. The Zadok's scale is therefore described in detail in this section.

The Zadok's growth scale: a decimal code

The Zadok's growth scale is based on ten principal growth stages listed in Table 2.2.

Table 2.2 – The ten principal decimal codes (see Table 2.3 for details).

0	Germination
1	Seedling growth
2	Tillering
3	Stem elongation
4	Booting
5	Ear emergence
6	Flowering
7	Milk development
8	Dough development
9	Ripening

Each scale comprises two digits, the first indicating the growth stage, e.g. 1 or 2, and the second, the number of plant parts (leaves or tillers) or secondary stages of development. This extends the scale from 00 to 99. For example, a Z13 indicates a seedling with three leaves.

The full decimal codes are reproduced in Table 2.3. However, in practical application, the most important stages are Seedling Growth (1), Tillering (2) and Stem Elongation (3) which span the time when most problems arise and most management decisions must be made.

Using the Zadok's code

Like all growth scales, the decimal code includes certain conventions and requires some practice. The scale is based on observations of individual plants rather than the general appearance of the crop. Therefore, it is essential to obtain a representative sample of plants from the crop.

Because leaf production, tillering and even stem extension may be occurring together, a number of different decimal codes can be applied to the same plant. This may appear confusing at first, but only represents what is happening in the crop. For the purposes of reporting the growth stage, only the most advanced decimal code need be used.

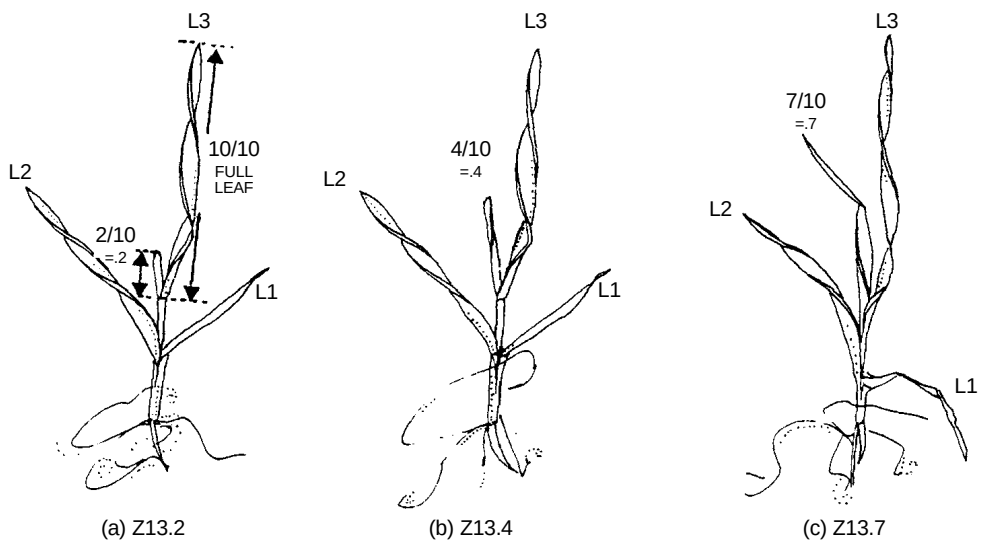
A general description of the principle decimal code is given in the Sections below, and complete details are given in Table 2.3.

Seedling growth Z10 to Z19

After the crop emerges, the decimal codes are determined by counting leaves (Table 2.3). There are some important rules:

- Leaves are numbered from the bottom of the plant, i.e. the first, oldest leaf upward (Figure 2.2)

Figure 2.5



Zadok codes for seedlings at different stages of leaf emergence (from AGWEST and 3 Tonne Club).

GROWTH SCALES FOR IDENTIFYING PLANT DEVELOPMENT

(continued)

- Only leaves arising on the mainstem are counted and care must be taken to exclude tillers and their leaves.
- A leaf can be described as unfolded or fully emerged when its ligule has emerged from the sheath of the preceding leaf.

A further subdivision is possible by scoring the youngest emerging leaf in tenths, judging its size relative to the preceding leaf. Thus Zadok codes of Z13.2, Z13.4 and Z13.7 describe seedlings with three fully emerged leaves plus a fourth leaf which is 0.2, 0.4 and 0.7 of the length of the third leaf respectively (see Figure 2.5a,b,c). Similarly, Z13.9 describes a seedling very close to having 4 fully-emerged leaves.

Common Western Australian wheat cultivars form between 8 and 14 leaves on the main stem. However, because older leaves die and the growth of tillers makes leaf counting difficult, it is seldom possible to ascertain the leaf number beyond Z16, i.e. the 6-leaf stage.

Tillering Z20 to Z29

The first tiller usually appears between the 3- and 4-leaf stage Z13-Z14. Tillers should be counted when they emerge from the sheath of the subtending leaf.

The important rules for counting tillers are:

- Count only tillers, not the mainstem
- Count a tiller only when it emerges from the sheath of the subtending leaf.

Tillering is not a good guide to the development stage of the plant because it is very dependent upon the nutrition and density of the crop.

To best indicate leaf plus tillering development, Zadok codes may be combined. For example, a plant with 3 leaves fully emerged and the 4th leaf at 0.3 (Z13.3) which is also tillering (code 2) with one (1) tiller is represented by the combined code Z13.3/21 (See Figure 2.6a). Other examples of plants with 4-5 leaves and 2-4 tillers are exemplified in Figure 2.6b,c.

Stem elongation Z30 to Z39

Stem elongation occurs by growth of the internodes of the stem. When elongation starts, an internode in the middle of the crown grows to a length of 1-2 cm and the node above it swells and hardens to form the first joint of the stem. Stem elongation is easily detected by splitting the stem with a sharp knife and identifying the nodes as obstructions to the cavity of the hollow stem.

Z30 equates with 'ear at 1 cm'. This code is widely used to signify that the plant is about to enter the phase of rapid stem elongation. This is a key stage for the crop because this is the time of most rapid growth and nutrient uptake.

Rules of scoring stem elongation are:

- 'Ear at 1 cm' (Z30) occurs when the length of the stem reaches 1 cm. The stem length is measured by splitting open the shoot and measuring the distance between where the lowest leaves are attached and the tip of the ear.
- 'First node detectable' (Z31) occurs when an internode of 1 cm or more is present.

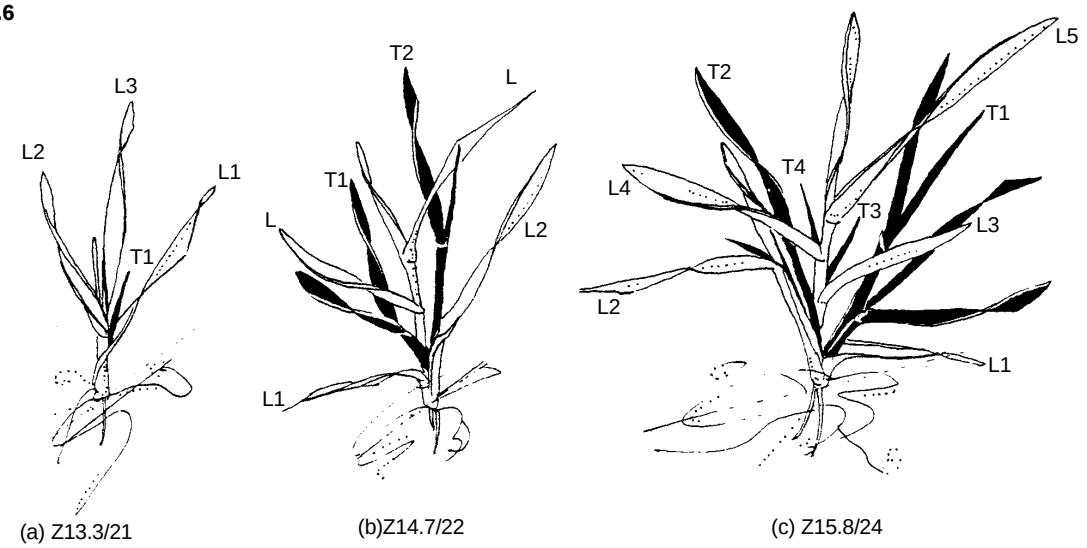
Booting Z40 to Z49

Booting stages describe the appearance of the upper portion of the stem at the flag leaf sheath. The *flag leaf* is the last leaf to develop on a cereal plant and it is located just below the ear. As the ear enlarges and moves upward through the shoot, the flag leaf sheath appears swollen and is called the *boot* (Plate 2.1(a)).

Ear emergence Z50 to Z59

Stages 50 to 59 describe the emergence of the ear from the boot. For example, Z55 means that half of the ear has emerged from the sheath and is above the ligule of the flag leaf. At Z59 the ear has fully emerged (Plate 2.1(b)).

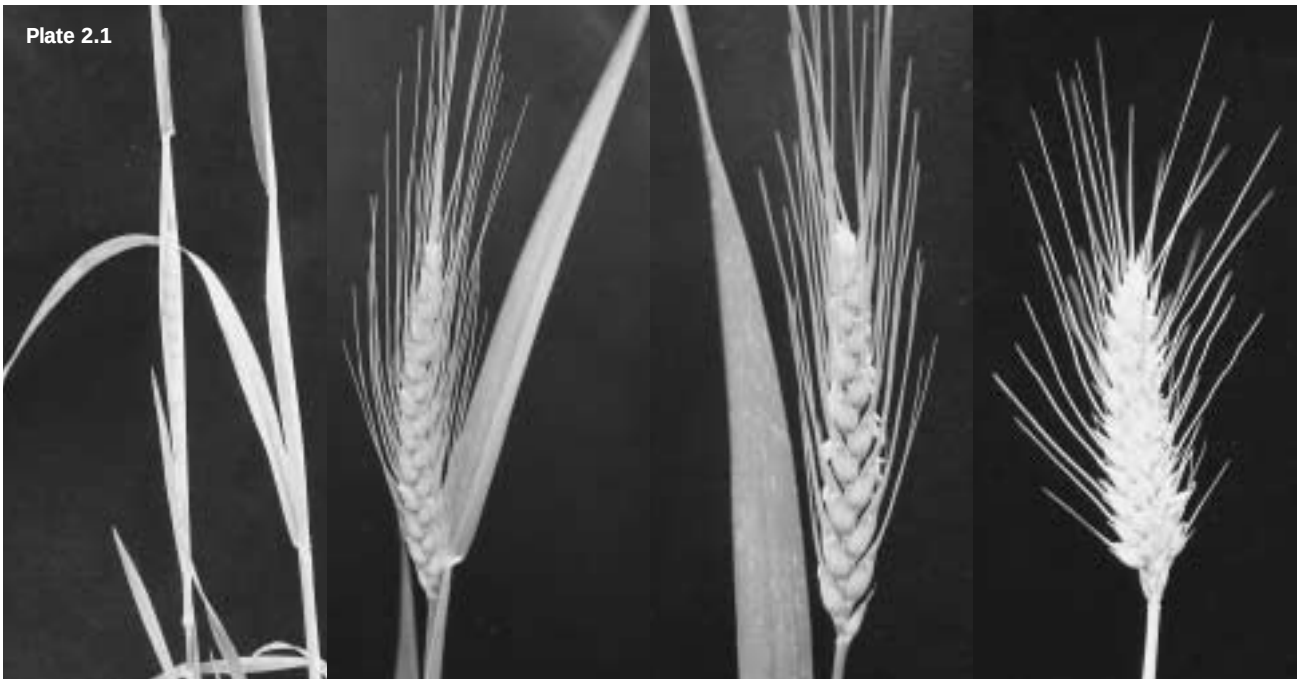
Figure 2.6



Zadok codes for plants at different stages of leaf and tiller emergence (from AGWEST and 3 Tonne Club).

■ GROWTH SCALES FOR IDENTIFYING PLANT DEVELOPMENT

(continued)



(a) A booting wheat plant (Z49 and Z45 respectively). Note swollen top of stem due to emerging ear.

(b) Complete ear emergence (Z59).

(c) Anthesis (flowering; Z65).

(d) Ripening (Z93).

Anthesis (flowering) Z60 to Z69

Anthesis means the opening of the floret or grass flower. Florets usually open in the early morning and remain open for only a short time. Wheat is self-fertilising, and the anthers or pollen sacs within each floret usually shed their pollen and fertilise the ovary shortly before anthesis.

Anthesis is usually scored when anthers are seen hanging from the spikelet (Plate 2.1(c)). These appear first in the middle of the ear and spread toward the top and base. In very dry conditions, stem extension is restricted and anthesis may occur as the ears are emerging, or even within the boot.

Milk and dough development Z70 to Z89

Stages 70 to 89 describe grain development. The stages are scored by subjective assessment of the amount of solids in the grain "milk", and subsequently the stiffness of the grain "dough".

Grain growth for 7 to 14 days after fertilisation is mainly growth of the ovary wall and the formation of the cells of the endosperm which will later be filled with starch. This early development is scored as 'Kernel watery ripe' Z71 (Plate 2.2a). Then starch starts to be deposited in the kernel and the ratio of solids to liquids determines the early (Plate 2.2b), medium (Plate 2.2c) and late milk stages.

Dough development (Z80 to Z89) follows when no liquid remains in the grain. At this time, the grain proceeds through stages of early, soft (Plate 2.2d) and hard dough (Plate 2.2e)

Ripening Z90 to Z99

Grain physiological maturity, the point where there is no further deposition of materials in the grain, occurs at about the hard dough stage. At this stage the grain has lost its green chlorophyll colour and turned brown. The grain still has a high moisture content and depending on weather conditions, it may be several days or several weeks until the grain is ready for machine harvest – Z93 (Plates 2.1d and 2.2f).

■ GROWTH SCALES FOR IDENTIFYING PLANT DEVELOPMENT

(continued)

Plate 2.2(a) *A recently pollinated carpel of wheat. The collapsed stigmas are still visible. Rapid cell division is taking place. Water ripe stage (Zadok's 71).*

Plate 2.2(b) *The grain has grown almost to its full length and is about one tenth of its final dry weight. Early milk stage (Zadok's 73).*

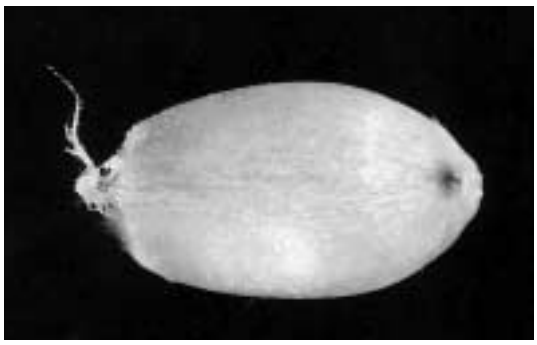


Plate 2.2(c) *A half grown grain of wheat. Medium milk stage (Zadok's 75).*

Plate 2.2(d) *A grain at about maximum fresh weight. The green colour is beginning to fade. Soft dough stage (Zadok's 85).*

Plate 2.2(e) *A grain at maximum dry weight. The green colour has completely gone. Hard dough stage (Zadok's 87).*

Plate 2.2(f) *A harvest-ripe grain (Zadok's 93).*

Grain development in wheat modified from Kirby and Appleyard (1987) Cereal Development Guide.

GROWTH SCALES FOR IDENTIFYING PLANT DEVELOPMENT

(continued)

Table 2.3 – The complete Zadok's growth scale and how to apply.

0 Germination

00: Dry seed
01: Start of water absorption
03: Seed fully swollen
05: First root emerged from seed
07: Coleoptile emerged from seed
09: First green leaf just at tip of coleoptile

1 Seedling Growth

Count leaves on mainstem only. Fully emerged = ligule visible. Sub-divide the score by rating the emergence of the youngest leaf in tenths. For example, 12.4 = two emerged leaves plus the youngest leaf at 4/10 emerged.

10: First leaf through coleoptile
11: First leaf emerged
12: 2 leaves emerged
13: 3 leaves emerged
14: 4 leaves emerged
15: 5 leaves emerged
16: 6 leaves emerged
17: 7 leaves emerged
18: 8 leaves emerged
19: 9 leaves emerged

2 Tillering

Count visible tillers on mainstem; i.e. number of side shoots with a leaf blade emerging between a leaf sheath and the mainstem.

20: Mainstem only
21: Mainstem and 1 tiller
22: Mainstem and 2 tillers
23: Mainstem and 3 tillers
24: Mainstem and 4 tillers
25: Mainstem and 5 tillers
26: Mainstem and 6 tillers
27: Mainstem and 7 tillers
28: Mainstem and 8 tillers
29: Mainstem and 9 or more tillers

3 Stem elongation

Generally count swollen nodes that can be felt on the mainstem. Report if dissection is used.

30: Youngest leaf sheath erect
31: First node detectable
32: Second node detectable
33: Third node detectable
34: Fourth node detectable
35: Fifth node detectable
36: Sixth node detectable
37: Flag leaf just visible
39: Flag leaf ligule just visible

4 Booting

Score the appearance of the sheath of the flag leaf.

41: Flag leaf sheath extending
43: Boots just visible swollen
45: Boots swollen
47: Flag leaf sheath opening
49: First awns visible

5 Ear emergence from boot

51: Tip of ear just visible
53: Ear 1/4 emerged
55: Ear 1/2 emerged
57: Ear 3/4 emerged
59: Ear emergence complete

6 Anthesis (flowering)

Generally scored by noting the presence of emerged anthers.

61: Beginning of anthesis (few anthers at middle of ear)
65: Anthesis half-way (anthers occurring half way to tip and base of ear)
69: Anthesis complete

7 Milk development

Score starch development in the watery kernel.

71: Kernel water ripe (no starch)
73: Early milk
75: Medium milk
77: Late milk

8 Dough development

Kernel no longer watery but still soft and dough-like

83: Early dough
85: Soft dough
87: Hard dough

9 Ripening

91: Grain hard, difficult to divide
92: Grain hard, not dented by thumbnail
93: Grain loosening in daytime
94: Over-ripe straw dead and collapsing
95: Seed dormant
96: Viable seed giving 50% germination
97: Seed not dormant
98: Secondary dormancy induced
99: Secondary dormancy lost

CHAPTER THREE

GERMINATION, VEGETATIVE AND REPRODUCTIVE GROWTH

Chapter Coordinator: T.L. Setter
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■ GERMINATION AND EMERGENCE

Tim Setter and Peter Carlton

The life cycle of the wheat plant is divided in this chapter into stages of germination, vegetative growth, and reproductive growth. Descriptions of these stages will involve frequent reference to structural features described previously in Chapter 2.

Germination and emergence are particularly important stages in the life cycle of the wheat plant. It is during these stages that the plant is most vulnerable to pests and environmental hazards such as waterlogging; and to management-induced problems such as depth of sowing, fertiliser toxicities and poor contact between seed and soil.

The primary aim of soil management and seeding practices should be to obtain uniform germination and rapid seedling emergence and establishment.

Germination

Germination is defined many ways and may include a wide range of seed and plant growth stages. Some definitions relate germination to the first emergence of the coleorhiza or primary root from the seed as it breaks through the pericarp. Other definitions, e.g. by the International Seed Testing Association (ISTA), state that germination must involve the complete development of a healthy seedling with all of the essential structures of a shoot and roots. For this chapter we will define germination as the former, where primary shoot and root tissues have just emerged through the seed coat following imbibition.

Moisture, suitable temperatures and adequate oxygen supply are all essential for germination of non dormant seeds. The dry seed first imbibes water and this is the trigger for both the biochemical and physical processes of germination. Water absorption during imbibition is purely a physical process, since even dead seeds can absorb water and swell during imbibition.

Fresh, mature wheat grains usually develop an innate dormancy which prevents germination in the ear if adverse weather conditions, such as high rainfall, occur before harvest. However, this dormancy disappears after a few weeks storage under dry conditions. Wheat cultivars differ in the degree of dormancy, and in some grasses (wild oats and some other grassy weeds), dormancy may prevent germination for years. When wheat seed is freshly harvested, dormancy may be broken by several methods, e.g. germination for the first 3 days at about 9°C, followed by germination at 20-25°C.

The minimum water content of seed for germination is about 35 to 40%. The minimum, optimum, and maximum temperatures for wheat germination are 3.5°-5.5°, 20°-25° and 35°C respectively.

An adequate supply of oxygen is also essential for germination of wheat. Oxygen is required to enable respiration of substrates in the endosperm to enable plant growth, development and survival. For wheat, the oxygen requirements for germination are usually met in a well drained soil due to rapid exchange of gases in soil with the atmosphere. However, when waterlogging or soil compaction occurs, oxygen supply may become limited. Most wheat cultivars grown in Western Australia have 50% death of seeds when they are germinated in waterlogged soil for 4 days. This seed death is due largely to limited oxygen supply, because gases diffuse 10,000 times more slowly in water than in air.

The processes of germination are complex, and they involve the release of hormones by the embryo, the stimulation of enzyme synthesis in the aleurone layer, the degradation of starch to sugars and their transfer through the scutellum to the growing embryo.

Physical swelling of the grain and rupture of the seed coat are the first outward signs of germination. The *coleorhiza* (a protective sheath of the radicle; c/f. coleoptile) and subsequently the primary seminal root are the first structures to appear from the base of the embryo and these are quickly followed by one or two pairs of lateral seminal roots.

As the first pair of seminal roots appear, the shoot, enclosed in the coleoptile, ruptures through the seed coat. The growing point and its attached leaves are pushed upward through the soil by elongation of an internode between the coleoptile and the growing point (Figure 3.1). Elongation of this internode ceases when the growing point is 1-2 cm below the ground surface, and the node associated with the first foliage leaf becomes the first node of the crown.

The variable elongation of this 'sub-crown internode' allows the crown of the plant to establish just below the soil surface no matter at what depth the grain is sown. This is important because the crown is the point of formation of the leaves and tillers which would otherwise have to emerge from whatever depth the seed is sown.

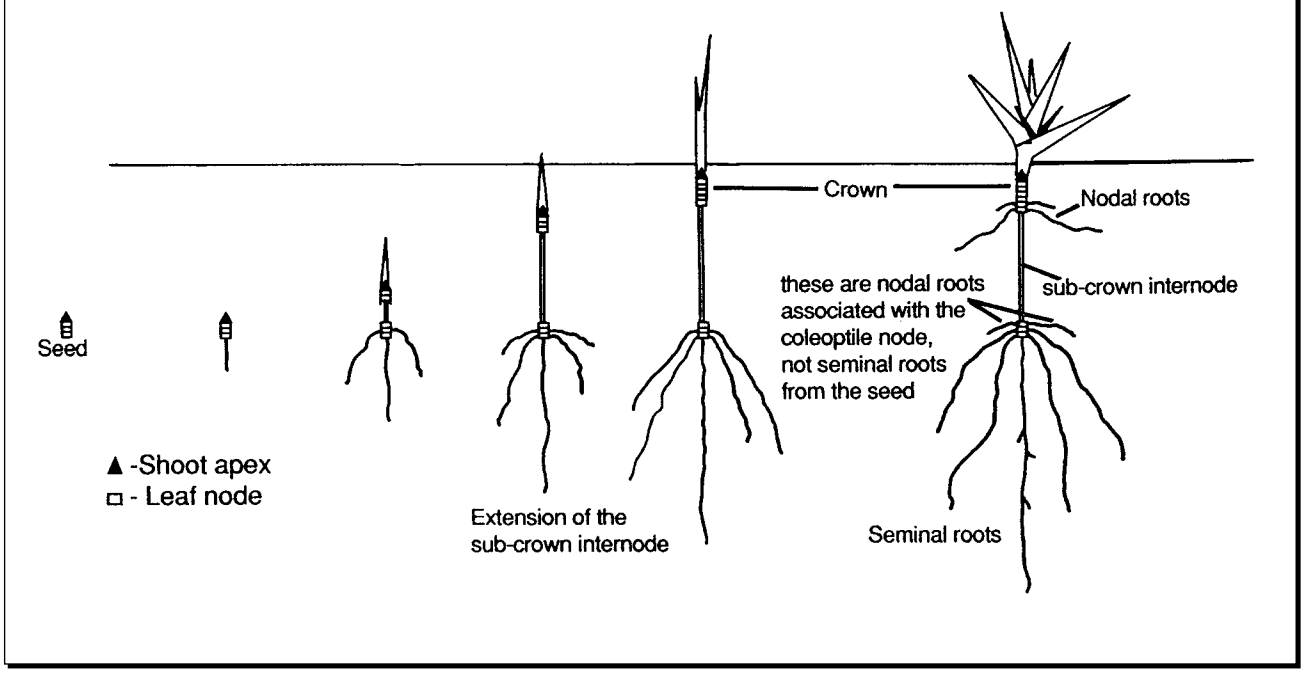
Seeds sown very deeply can show elongation of both the sub-crown internode, and the internode between the first and second foliage leaves, in order to bring the crown of the plant close to the soil surface.

Emergence

Growth of the coleoptile ceases as it reaches the surface and the tip of the first leaf appears through the pore at the tip. In addition to its protective role, the coleoptile also directs the shoot vertically upward. Very deep sowing (and the herbicide trifluralin) restrict the length of the coleoptile allowing the leaf to appear from the pore while still below the surface.

■ GERMINATION AND EMERGENCE *(continued)*

Figure 3.1



How wheat germinates and the seedlings establish (continued in Figure 3.7)

Cultivars differ in coleoptile lengths. Semi-dwarf wheats, in addition to shorter stems, usually also have shorter coleoptiles than the tall wheats grown in the past; and for this reason are more likely to emerge poorly if sown too deeply.

Cultivars with short coleoptiles (less than 60 mm) like Cascades, Eradu and Tammin, will take longer to emerge if sown deeply, and they may fail to emerge if sown at depth greater than their coleoptile length. Cultivars like Cadoux, Halberd and Westonia have long coleoptile lengths up to 90 mm.

Sowing depth is the key management practice in ensuring uniform, rapid emergence and seedling establishment. The seedling has the capacity to establish from as deeply as 15 cm, but field trials show that sowing below 6 cm generally reduces grain yield.

Depth of sowing is particularly important because:

(i) deeper seed placement delays emergence – equivalent to sowing later, and

(ii) seedlings emerging from greater depth are weaker and tiller poorly.

■ VEGETATIVE GROWTH

Germination and emergence is followed by the vegetative phase of the plant's life cycle. The plant is developing the structures and beginning to gather the nutrients that will support it during the remainder of the life cycle. The first formed leaves emerge, new leaves are still being formed on the shoot apex, tillering is commencing, and the plant's root systems are beginning to explore the soil.

Formation and emergence of leaves

Within the seed, the embryo already has three leaf primordia present, and upon germination the apex is activated and a series of new leaf primordia are formed.

Each primordium forms on the flank of the apex as crescent-shaped ridges and spreads laterally to encircle the apex. This encirclement occurs within the limiting confines of the preceding leaf primordium, and growth of the leaf is essentially upward, parallel with the axis of the plant.

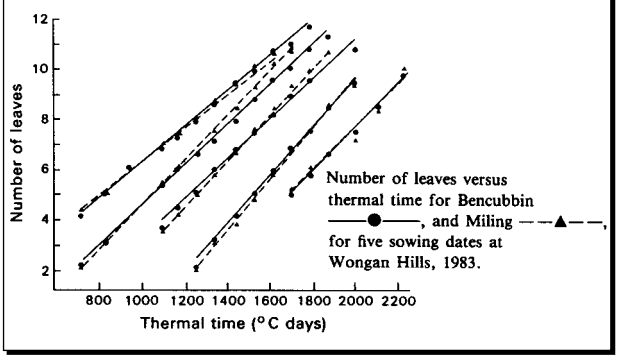
As few as five, or as many as 20 leaves may be formed by the shoot apex before it forms the ear, but because the rate of leaf formation is more rapid than the rate at which mature leaves appear, immature leaves accumulate around the apex developing within the shoot. Therefore, although leaf initiation ceases when the ear is initiated, leaves continue to emerge from the shoot until shortly before flowering.

Rate of leaf emergence

Leaf emergence is the key to understanding and predicting the development of the cereal plant because leaf emergence is closely coordinated with growth and development changes that are often difficult to see within the plant. Equally important, leaves emerge at a rate set by ambient temperature, and by predicting leaf number it is possible to predict the developmental stage of a cultivar.

The rate at which leaves appear depends on the daily temperature. Thus when the weather is cold, leaves appear slowly, and leaf appearance is more rapid when the weather is warm. However, when leaf appearance is measured in thermal time[1] – accumulated day degrees (°Cd) – there is a linear relationship between leaf number and accumulated thermal time. An example of calculating thermal time in °Cd is given in Table 3.1, and the relationship of leaf emergence to thermal time can be seen in Figure 3.2.

Figure 3.2



Leaf emergence expressed in terms of thermal time.

The slope of this relationship is the rate of leaf emergence expressed as "leaves per day degree". There is a constant thermal time between the emergence of one leaf and the emergence of the next, and this interval is termed the 'phyllochron'.

Wheat crops sown in early June have a phyllochron of about 100 °Cd, equivalent to a rate of leaf emergence of about 0.01 leaves per °Cd. If the daily mean temperature is say 10°C, a leaf will thus take 10 days to emerge. At a mean temperature of 12.5°C, only eight days will be needed (100 °Cd divided by 12.5°C = 8 days).

Although the rate of leaf emergence is constant for given cultivars and sowing time, it varies systematically with sowing date. The reason for this is unknown. One suggestion is that the rate is set when the crop emerges and the first leaf is exposed to daylight. Another suggestion is that the rate at which day length is changing is the environmental cue that sets the rate of leaf emergence; and although it cannot account for all observations it has

Table 3.1 – Example of how to calculate thermal time (°Cd). In this example, 89.9 °Cd or heat units were accumulated during the week, almost enough to allow the appearance of one leaf (about 100°Cd).

Date	Minimum	Maximum	Mean	Accumulated 1.c.(d)
11 June (sowing)	5.6	16.2	10.9	10.9
12 June	7.2	18.5	12.8	23.7
13 June	6.7	17.9	12.3	36.0
14 June	11.9	15.6	13.8	49.8
15 June	10.6	16.4	13.5	63.3
16 June	8.5	17.9	13.3	76.6
17 June	7.1	19.3	13.2	89.8

[1]*Thermal time*
Accumulated temperature or 'thermal time' is calculate as the mean daily temperature minus a base temperature. The base temperature is usually taken to be 0°C.. The thermal time is then calculated as: [(maximum °C + minimum °C) /z] for each day, then summed for all the days involved.

VEGETATIVE GROWTH *(continued)*

proven useful in developing equations to predict the rate of leaf emergence.

For very early or very late sown crops, the rate of change in daylength at the time of emergence will be significant and will lead to a lower (for early crops) or greater (for late sown crops) rate of leaf emergence.

For practical purposes, the rate of leaf emergence for normal commercial crops will be about 0.01 leaves per °Cd; equivalent to a phyllochron interval of 100 °Cd per leaf.

Tillering

Tillers arise from buds formed in the axils of the leaves. Structurally they are identical to the mainstem of the plant, and when a tiller first appears it is enclosed in a modified leaf – the prophyll – similar to the coleoptile which enclosed the mainstem as it emerged from the seed.

Tillers are produced in strict sequence and each has a narrow "window" of developmental time in which it can appear. The tiller at a given leaf will appear between 2.5 and 3 phyllochrons after that leaf has appeared. Thus the first tiller (T1) will appear when the mainstem of the wheat plant has about 2.7 leaves; the second tiller (T2) will appear when the plant has about 3.7 leaves, and so on.

Leaf production on tillers occurs at the same rate (i.e. with the same phyllocron interval) as the mainstem, provided the plant is not under stress.

Tillers are identified by numbers describing their position on the plant. Thus the first tiller, appearing from the axil of leaf 1, is called T1; the tiller appearing from the axil of leaf 2 is T2, etc. Sub-tillers follow the same scheme, and a tiller appearing from the axil of the first leaf of T1 would be called T11. The coleoptile tiller is T0, and the tiller arising from the prophyll of T1 would be T10.

Production and growth of tillers is very sensitive to environmental and nutritional stress. Stress delays tiller emergence, and slows growth of the tillers. If stress is severe, a tiller may 'miss' its allotted developmental 'window' and will then never appear. The positions and size of tillers therefore form a record of the history of stress experienced by the plant.

Tiller survival

In most wheat crops, the plant produces "non productive tillers" which do not form ears and grain. Many research programs aim to reduce these non productive tillers to try and increase yields of new cultivars. However, non productive tillers may act as reserves for nutrients and carbohydrates. They may also enable recovery if the productive tillers are damaged or destroyed during crop growth.

Tiller production depends on cultivar, and environmental conditions, but tillers are produced until about the start of stem elongation, when tiller numbers reach a maximum. Tiller numbers then decline until anthesis, thereafter remaining more or less constant until harvest.

Light interception

Until the first two leaves are unfolded, plant growth depends mainly on the stored food in the endosperm of the grain. After that, the crop depends entirely on the capture of solar radiation by the leaves and other green tissues to fuel the process of photosynthesis.

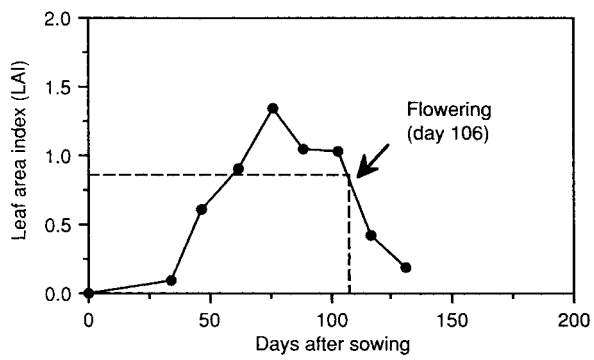
Leaves are the primary organs for radiation interception, and the growth rates of crops are closely related to the amount of solar radiation captured by the leaves. Growth is determined by both the area of leaf as well as leaf shape, inclination and arrangement in the canopy of the crop.

Leaf area is measured as the leaf area index (LAI), this is the ratio of the area of leaf to the land area. For example, a crop with an LAI of 1.5 has 1.5 square metres of leaf for each square metre of ground. LAI development for a typical wheat crop in the eastern wheatbelt is illustrated in Figure 3.3.

Initially, LAI increases only slowly in the cool winter, then increases rapidly to a maximum at about ear emergence. The leaves of cereals have only a limited life and lower leaves senesce and die as they are shaded by the leaves in the canopy above. Usually only the 3 to 4 youngest leaves on a stem are green and active.

Leaf orientation and display are important for the efficient capture of radiation. While a LAI of 1.0 could theoretically intercept all radiation (if the leaf was laid flat on the ground), LAI must reach at least 3 before nearly all radiation is intercepted and the rate of growth becomes limited by light. This seldom occurs for very long in Western Australia.

Figure 3.3



Leaf area index of a wheat crop grown at Merredin, WA.

[(Maximum °C + Minimum °C)/2] for each day, then summed for all the days involved.

■ VEGETATIVE GROWTH *(continued)*

Seminal roots

The first root to appear during germination is the radicle which emerges through the root-sheath (coleorhiza). This is followed shortly by a pair of seminal roots. These three roots, plus a second pair of seminal roots, grow rapidly probably because of their well developed vascular connections to the scutellum.

In poorly developed seeds, one or both of the second pair of seminal roots may be absent, whilst in well developed seeds a sixth root may appear at this scutellar node.

Thus, a minimum of three and a maximum of six seminal roots can appear from the seed. These roots are fine (0.5 mm diameter), and fibrous by comparison with the nodal roots.

Nodal roots

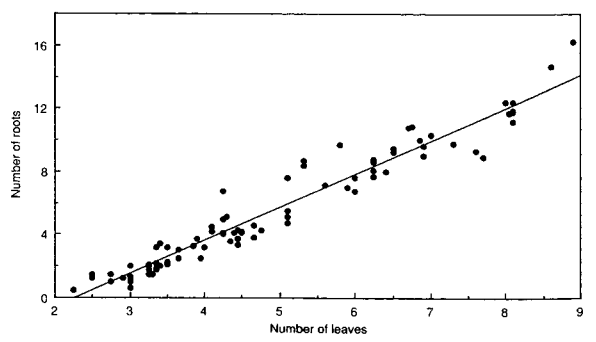
The first nodal roots can appear as a pair of roots at the coleoptile node, and as such are often confused with seminal roots.

The first true 'crown' roots appear as a pair of roots on opposite sides of the stem at the level of the first leaf node, and emerge about three phyllocrons after the leaf has emerged. Thereafter, each main stem node up to node 4 or 5 produces a pair of nodal roots.

Tillers also produce nodal roots, with a single root appearing at 90° to the main stem roots about two phyllocrons after emergence of the tiller, plus a pair of roots another phyllocron later. Pairs of nodal roots then appear on successive nodes at the same rate as leaves emerge.

There are thus strong connections between the numbers of leaves, tillers and nodal roots on a plant, with almost twice as many root axes as leaves (Figure 3.4).

Figure 3.4



Relationship between the number of roots and the number of leaves on the wheat plant.

The growth of nodal axes depends on the health of the plant, and environmental conditions, particularly soil moisture and fertility.

Many of these roots appear in spring when the soil at the surface is starting to dry rapidly, and above the depth of placed fertiliser; their growth into drying soil is often slow, and many axes are ineffective in taking up water and nutrients.

As tiller survival is linked to the functioning of some of these late formed roots, it is clear that late planted crops will have less chance of either producing (see Tillering, above) or maintaining tillers.

Nodal roots are typically thicker (>1 mm) and fleshier than seminal roots, although this distinction becomes less obvious below the surface layers of the soil profile.

Root growth

Roots elongate by division and expansion of cells in a meristem at the tip of each root; and the rate of growth depends on temperature, and the resistance imposed by the soil. The resistance of the soil to root penetration depends on the soil texture, soil moisture content, and the amount of cultivation.

In southern Australia root growth rates are 1.0 to 1.5 cm per day; thus the seminal roots of wheat can reach at least 150 cm by anthesis, and even deeper by the time of physiological maturity.

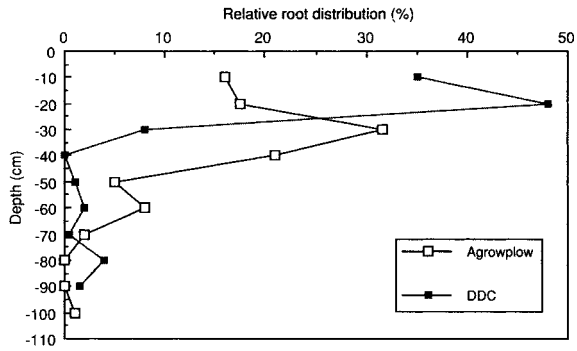
In the early stages of growth, root weight is equivalent to shoot (above ground) weight; but by anthesis, root weight accounts for only about one third of total plant weight.

Roots start to branch (first order) about two phyllochrons after the root has appeared. The first order branches develop branches (second order) a further two phyllocrons later, and a third order of branching can develop on the oldest seminal roots.

This pattern of elongation and branching means that a considerable length of root can develop on each plant: a typical value for cereals in Western Australia is 4.0 km per m^2 of ground surface.

Root lengths are often expressed as a root length density (cm of root per cubic cm of soil), and typical values for wheat in Western Australia range from 5 cm/cm^3 in the first 10 cm of the soil profile to less than 0.1 cm/cm^3 at 100 cm depth.

Figure 3.5



Effect of soil strength on wheat root distribution on a deep yellow sand at Wongan Hills, WA. Agrowplow plots, tilled to 30cm, had lower soil strength and more roots at depth than direct drilling (DDC).

■ VEGETATIVE GROWTH *(continued)*

Patterns of root distribution of wheat established either by direct drilling, or after deep ripping are shown in Figure 3.5. Where soil resistance is high after direct drilling, roots are more abundant near to the soil surface; whereas after ripping, there are more roots at depth, and roots are deeper in the profile.

Shoot and root dry matter production

Dry matter production or net photosynthesis of wheat is determined by the sum of gross photosynthesis, photorespiration, and "dark" respiration (or simply "respiration"). Gross photosynthesis involves the conversion of water and carbon dioxide gas (CO_2) from the atmosphere into carbohydrates, dry matter and oxygen (O_2). This is achieved mainly by leaves but also by other green tissues of wheat shoots in the light.

Photorespiration is the light-dependent conversion of specific carbon compounds derived from photosynthesis into more diverse substances required for plant growth. In comparison, respiration is the conversion of substances in the light or the dark, which is specifically linked to energy production essential for growth and survival. Both photorespiration and respiration require oxygen and both these processes produce carbon dioxide.

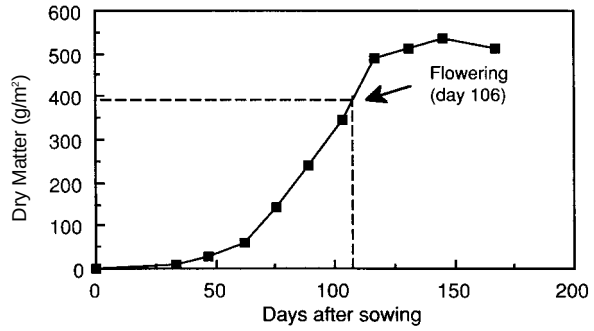
The oxygen requirement of plants is how some environmental stresses affect plant growth. For example, reduced oxygen supply in soils during waterlogging is why waterlogging has such adverse effects on crops. Limited oxygen reduces respiration, which reduces energy production, which reduces growth and survival of roots, and this adversely affects shoots.

Respiration losses by crops commonly account for about half of the carbon which is fixed in photosynthesis, while photorespiration reduces the amount of carbon fixed by wheat a further 15-20%.

Shoot dry matter

Dry matter accumulation of shoots is initially slow (see Figure 3.6), but by August in Western Australia the wheat crop canopy has usually closed (LAI = 2 to 3) and a period of rapid growth ensues. Provided soil water storage is adequate, crop growth is primarily governed by the intercepted solar radiation and temperature.

Figure 3.6



Dry matter accumulation of a wheat crop at Merredin.

In Western Australia, maximum crop growth rates of 160 to 180 kg/ha per day occur during the life cycle, before these rates decline due to leaf senesce during grain filling. In countries where radiation and temperature are more ideal, cereal crop growth rates can be more than 2 times these values.

Root dry matter

Plants must grow extensive root systems to explore the soil profile and collect water and nutrients. Usually more dry matter is allocated to roots than shoots in the early growth stages. For Kulin, in an experiment at Merredin, 65% of the total plant dry matter was found in the roots at 34 days after sowing, but only 35% occurred in roots at anthesis (Table 3.2).

The total amount of dry matter in the roots is substantial. In terms of returning organic matter to the soil, the root dry matter may equal the contribution of straw retained after harvest.

Table 3.2 – Dry matter (g/m²) in the roots and shoots of a wheat crop grown at Merredin, WA.

Trait	34 days	62 days	104 days (anthesis)
Dry matter			
Roots	22	75	280
Shoots	12	69	509
Root to shoot ratio	2/1	1/1	0.5/1
Root % total dry matter	65	52	35

■ REPRODUCTIVE GROWTH AND GRAIN FILLING

The vegetative stage of the life cycle ends when the shoot apex ceases forming leaves and begins the formation of the ear. This event, 'ear initiation' (See Chapter 2) is a key point in the life cycle because the maturity of the cultivar – whether it is early or late in a particular environment – is determined largely by the timing of ear initiation.

Formation of the ear ends when a 'terminal spikelet' is formed. As this stage is reached, stem extension is beginning and the plant is entering the phase of most rapid growth and nutrient uptake. Stem extension ceases at about the time of anthesis when floret fertilisation occurs and grain growth begins.

Ear initiation

After germination, new leaf primordia are formed on the shoot apex for only a short time. The total number of leaves formed by the apex may be as few as five or as many as 20, but in current Western Australian cultivars is usually only 8 or 9.

Elongation of the apex is the first sign that the production of leaf primordia is about to cease and the apex is reorganising to form the ear. This stage requires dissection of the shoot to observe (Plate 3.1).

Elongation of the apex is followed by the appearance on the apex of a series of ridges similar to the earlier leaf primordia. These develop further to form a structure where the leaf and spikelet primordia are present together in a 'double ridge'. The lower (leaf) ridge disappears, whilst the larger, upper structure develops as a spikelet (Plate 3.2).

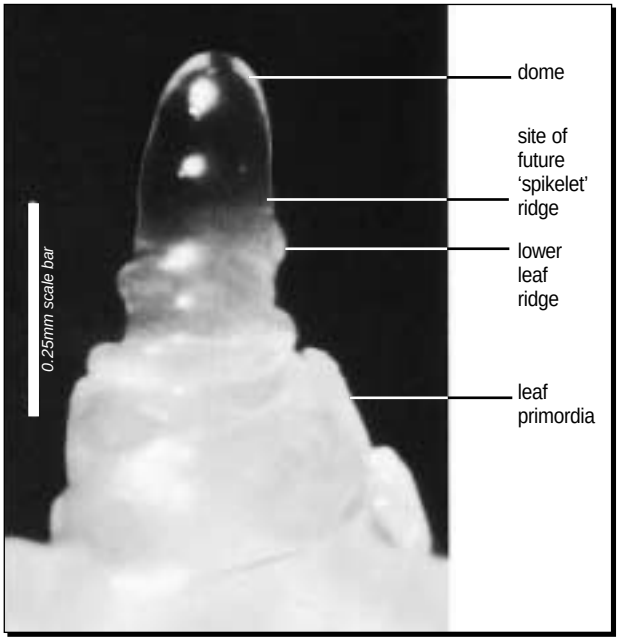


Plate 3.1 *Shoot apex at late vegetative. Primordia at base will continue to grow into leaves but the development of leaf ridges further up the dome will be arrested. (Adapted from Kirby and Appleyard; Cereal Development Guide, 1984).*

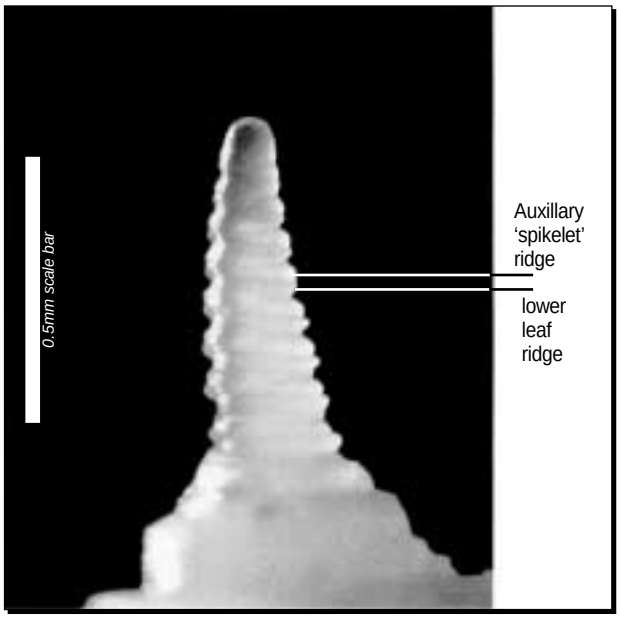


Plate 3.2 *Shoot apex at double ridge. Development of leaf primordia arrested and spikelet primordia can be identified. (Adapted from Kirby and Appleyard; Cereal Development Guide, 1984).*

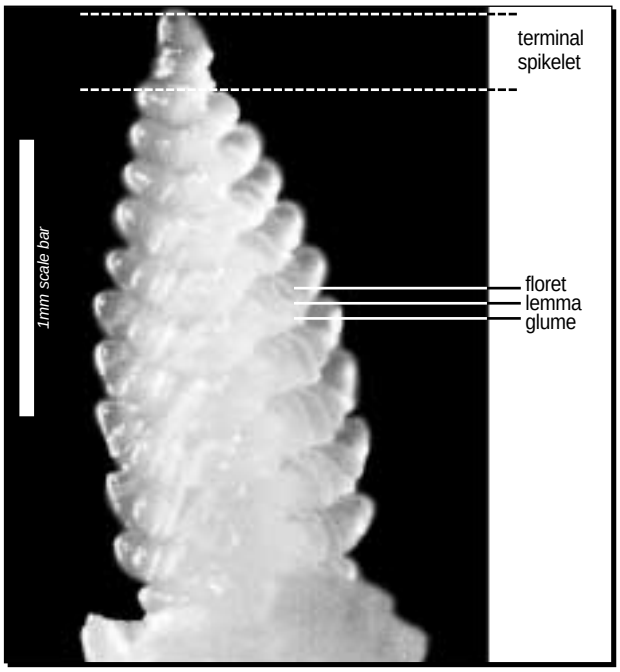


Plate 3.3 *Shoot apex at terminal spikelet. Upper most primordia develop into the parts of a spikelet. (Adapted from Kirby and Appleyard; Cereal Development Guide, 1984).*

The first double ridges, and hence the first spikelets, form in the centre of the elongated apex and new spikelets are then initiated progressively toward the top and bottom of the apex. Spikelet initiation ceases when the apical dome forms a final, single 'terminal spikelet' orientated at right angles to the two parallel rows of spikelets on the apex (Plate 3.3).

■ REPRODUCTIVE GROWTH AND GRAIN FILLING *(continued)*

Detecting the switch from leaf to ear formation.

The primordia that are to form the leaves and spikelets appear on the apex in two distinct phases which differ in the rate at which primordia are initiated. The point at which the rate changes is generally considered to indicate 'ear initiation' and the number of primordia formed by the apex up to this point will equal the final leaf number.

The change in rate of primordia formation and hence ear initiation can be detected only in retrospect. However 'double ridge' (Plate 3.2), which can be detected by dissection under a microscope, closely follows ear initiation and the two stages, for practical purposes, have been considered the same.

Dissection, however, is not essential to establish ear initiation because for each cultivar there is a consistent relationship between ear initiation and the number of visible emerged leaves on the stem. Note in the Zadok's Growth Scale described in Chapter 2, there is no description of ear development until after booting.

Maturity of cultivars.

The significance of ear initiation is that differences in life cycle between early, midseason and late maturing cultivars are determined by differences in the timing of ear initiation.

Short duration (early) cultivars come to ear, flower and mature quickly because ear initiation occurs after only 6-8 leaf primordia have formed. Mid-season cultivars generally form 10-11 leaves, and the late maturing cultivars 12-14 leaves before ear initiation occurs.

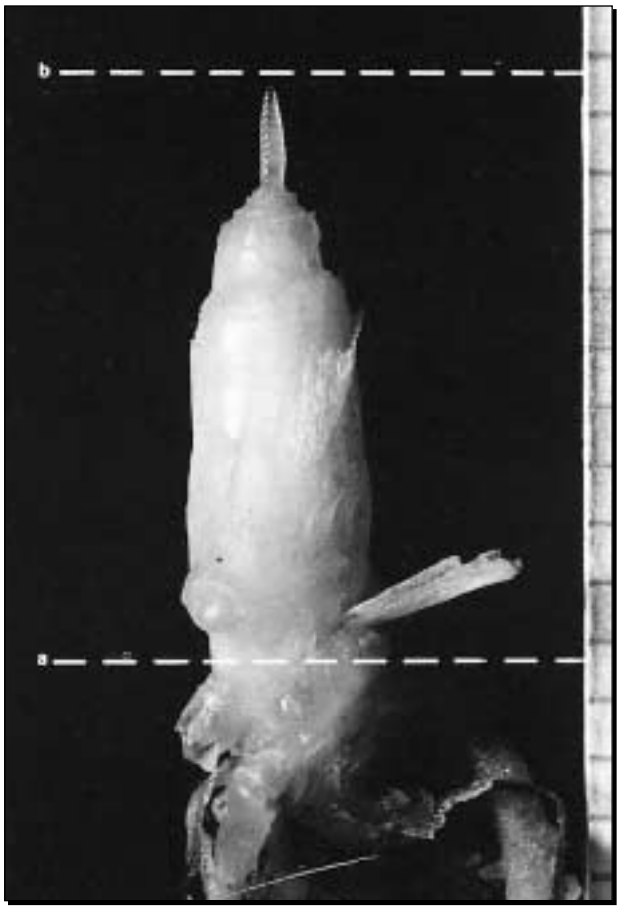


Plate 3.4 *Ear at 1cm. Designates the beginning of stem elongation (Zadock's 30 stage).*

Stem elongation

Rapid stem elongation occurs shortly before the terminal spikelet stage in wheat (Plate 3.3). In southern Australia eight to 14 leaves and about 18 spikelets have been formed, however the tiny embryonic ear is still only 1-2 mm long, and is still located within the crown of the plant below the ground surface.

The beginning of stem elongation is described as "Ear at 1 cm" because, if the mainstem leaves are stripped away, the length from the base of the tiller/root insertion to the tip of the ear is 1 cm long (Plate 3.4). Ear at 1 cm is equivalent to Zadok's 30 stage (Chapter 2).

In the next phase, the ear and stem grow rapidly. Associated with this growth is the formation of florets within each spikelet and, later, the regression and death of some florets and spikelets and the death of some tillers. This phase is also the time of greatest dry mass increase and nutrient uptake of the plant.

Each leaf and spikelet is attached to a 'node' at the base of the stem where the vascular tissues of the leaf enter the stem. These nodes are stacked tightly, one above the other, and the structure of the stem can be likened to a pile of saucers, each saucer representing a node. Stem extension is the process of separating the nodes by expansion of the tissues between each node. i.e. expansion of the internodes.

Not all internodes expand. For an early maturing cereal, each mainstem will form eight leaves and only the four (or rarely five) uppermost internodes expand. This is illustrated in Figure 3.7.

In this example, the first internode to grow is that associated with leaf five. Cell division and cell expansion push the developing ear above the ground surface. This is 'Ear at 1 cm' (See Chapter 2, The Zadok's growth scale) and is a sign that the crop is entering the phase of most rapid growth. Internode five remains short, but as its growth slows, internode six begins to expand followed in turn by internode seven.

The final internode to expand is the peduncle, the internode above the flag leaf which is connected to the ear. Growth of the peduncle moves the ear upward within the 'boot' formed by the flag leaf sheath. "Booting", the swelling of the ear within the boot, is followed by "ear peep" where the ear emerges from the flag leaf. By continued growth of the peduncle, the ear is carried above the leaf canopy to reach flowering or anthesis.

■ REPRODUCTIVE GROWTH AND GRAIN FILLING *(continued)*

Figure 3.7

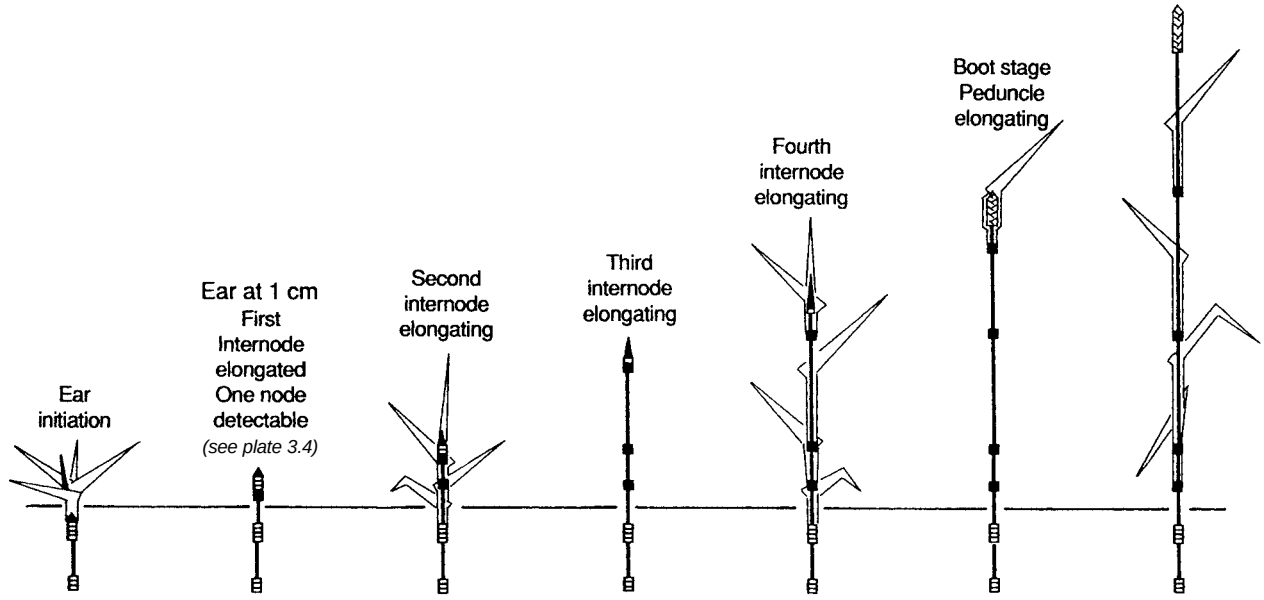


Illustration of stem elongation in wheat.

Floret formation

Initiation of the terminal spikelet marks the end of spikelet formation. Floret formation starts just before spikelet initiation ceases, and the first florets differentiate within spikelets in the lower – central portion of the spike. The central spikelet of an ear can initiate up to 10 floret primordia, however, the distally positioned spikelets initiate fewer florets.

In a typical wheat crop, only 30-40 % of florets set grains. After reaching a maximum, floret number is maintained for a short period, before the florets at either end of the spike shrivel and die. By anthesis, floret number remains stable.

Floret production and survival are important because they determine grain number which is closely related to grain yield. Floret survival is greatest when conditions favour assimilate production i.e. adequate water and nutrient supplies, optimum temperatures, and high solar radiation.

There is a critical period two to three weeks before anthesis, and this is when water stress and/or high temperature may greatly reduce the floret production and survival, greatly reducing the grain number per spikelet.

Anthesis

The final phase of the cereal life cycle begins with anthesis and ends with the development of mature grain. Anthesis (or flowering) is the bursting of the pollen sacs and the fertilisation of the carpel.

Wheat is self-fertilising and only after fertilisation do the glumes separate and allow the now empty anthers to appear on the outside of the ear.

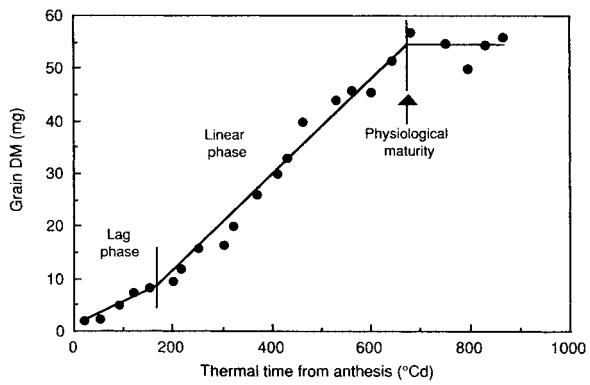
Grain growth

A wheat grain grows through three typical phases shown in Figure 3.8. After anthesis there is a 'lag' phase followed by a short period of exponential growth. During the lag phase the cells of the endosperm divide rapidly and the potential size of the grain is determined. This period lasts between 10 to 14 days (about 180 °Cd).

In the second phase, growth in dry weight is nearly constant (in thermal time) as starch is deposited in the endosperm and the grain contents take on a milk-like and then dough-like consistency. This phase lasts between 15 and 35 days.

The final phase begins when waxy substances are produced to block the vascular strands supplying the grain, and growth of grain ceases. This is physiological maturity (at about 700 °Cd).

Figure 3.8



Dry matter accumulation of a wheat kernal at Merredin, WA.

■ REPRODUCTIVE GROWTH AND GRAIN FILLING *(continued)*

After maturity, the water content of the grain drops rapidly depending on the weather conditions, eventually becoming dry enough (10 to 20% water content) to harvest.

Since most of the final weight of the grain is accumulated during the linear phase of growth, the rate of grain growth during this phase is highly correlated with the final weight of the grain. The absolute rate of grain growth during the linear growth period in the field ranges between 1.0 and 3.0 mg per grain per day, depending on the environment, cultivar and grain position within the spike.

Usually about 90% of the sugars required for grain growth comes from photosynthesis after anthesis. However, the plant may also store considerable materials in the stems and leaf sheaths as complex sugars (fructans) and these are re-mobilized during grain filling. When a crop is affected by drought, which decreases photosynthesis during grain filling, stem stored fructans may contribute up to 70% or more of grain weight.

Harvest index

The harvest index is the ratio of grain weight to total weight of the crop. For example, if a crop yields 1.4 t/ha and the total weight of the crop (grain plus straw) is 4.0 t/ha, the harvest index is 1.4/4.0 = 0.35 or 35%.

Harvest index is not really a component of yield because it can only be calculated after the crop has matured. It is sometimes useful, however, as a measure of how the yield was achieved.

A crop's potential harvest index may be determined by the growth rates of the ear and stem when the ear is being formed, that is, at about terminal spikelet stage. The potential could thus be raised by good crop husbandry which improves the growth rates of those structures.

Harvest index is usually low if growing conditions during grain filling are poor, as little grain is formed compared to the dry matter already grown by anthesis. Where grain is filled in cool weather with adequate water, harvest index will usually be high; but there are many exceptions such as when *Septoria* disease reduces grain weight and harvest index.

Yield components

Many factors limit yield in wheat. The final yield is an outcome of the interaction of genetic, environmental and crop management factors.

Although grain yield is the final product of all the growth and development processes during the life cycle of the crop, it can be conveniently divided into a number of sub-units called yield components.

The main yield components of a wheat crop are:

- The number of ears per square metre (E);
- The number of spikelets per ear, (Sp);
- The number of grains per spikelet (Gr); and
- The weight of an individual grain (Wg) in grams.

Grain yield in grams per square metre, can then be expressed in terms of its yield components as;

Yield (Y) = (E x Sp x Gr) Wg

The above equation suggests that if one component is increased then grain yield will be greater, but this is seldom the case as yield components partially compensate for each other. This 'yield component compensation' is discussed in detail later.

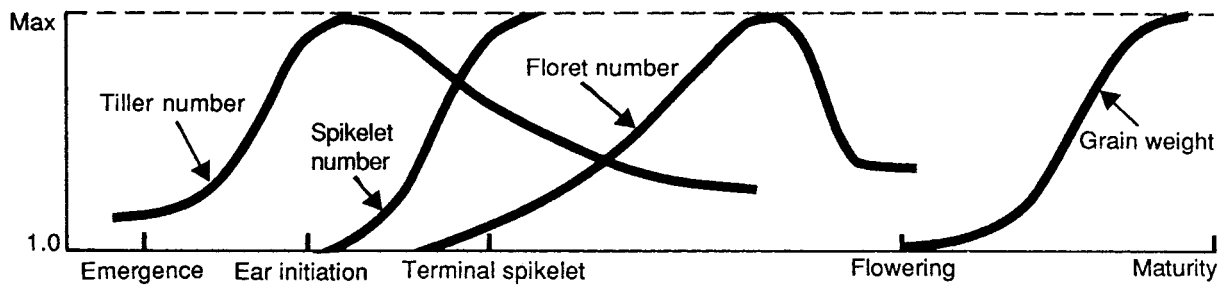
Past research demonstrates that the highest wheat yields are often the outcome of extreme values for one of the yield components, rather than a consistent set of ideal values for all these components. However, high grain number per m^2, whether from ears/m^2 or grains/ear, is an essential prerequisite for high yield.

Determination of yield components

The cultivar sets the potential for the yield components – tillering, spikelet number, the number of florets, and kernel weight. These are determined in a sequence throughout the life cycle of the crop, shown in Figure 3.9. This is not a simple process, as formation of different components may overlap, and frequently, over-production of a component at an early stage of growth is followed by decrease at a later stage.

Generally the plant's yield potential exceeds the final yield. Water, nutrients, temperature, light and other environmental factors at sub-optimal levels reduce one or

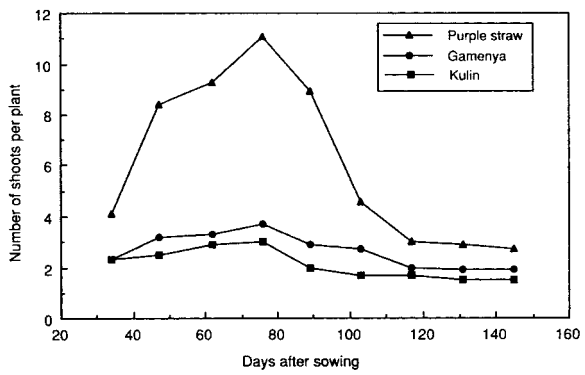
Figure 3.9



Representation of the development of the yield components through the life cycle of the crop.

■ REPRODUCTIVE GROWTH AND GRAIN FILLING *(continued)*

Figure 3.10



Tiller production of three wheat cultivars representing old purple straw, intermediate Gamenya and modern kulin cultivars.

more of the yield components – often by aborting some tillers or florets after they have been formed.

Management of the wheat crop should aim to maximize yield through an agronomic package (seed rate, sowing depth, sowing time, fertilizers, weed and pest control) consistent with the known environmental limitations.

Number of ears (E)

Ear number is the first yield component to be formed and is set by tiller number. Tiller production depends on cultivar and environmental conditions (in particular nutrition). In most wheat crops, the plant produces more tillers than survive to form ears and grain.

Tillers are produced until roughly the start of stem elongation (soon after the terminal spikelet stage), and the number then declines until ear emergence; thereafter remaining almost constant until maturity. Typical patterns of tiller production and decline for old and modern wheats grown in Western Australia are shown in Figure 3.10.

The reasons for tiller death are not known precisely, but are probably related to competition within the plant for dry matter, water and nutrients, particularly after stem elongation when growth increases rapidly.

Tillers are not capable of surviving alone until they have about three leaves, and are starting to develop their own nodal roots. In practice, only the first two or three tillers are likely to reach this stage before the plant ceases leaf and tiller production.

Modern wheats bred for and grown in Western Australia generally mature earlier than older wheats. They also produce fewer leaves on the main stem, consequently have fewer tillering 'sites' and produce few tillers. This strategy allows the plants to reach anthesis early in the season with minimal investment in vegetative structures, and subsequently to concentrate on development before moisture stress develops.

A plant that produces no tillers – the 'uniculm' wheat – in which all the plant's energies can be focused on maximizing grain numbers on a single stem – has, as yet, not produced more grain than conventional types. Such a plant lacks the flexibility required in rainfed field conditions to cope with stress, pests and disease.

Number of spikelets per ear (Sp)

Spikelets are formed when the shoot apex begins reproductive development when the apical dome elongates. In spring wheats this is when the main shoot has about 3 to 5 leaves. The number of spikelets per ear is set by genotype and environment, but for normal high yielding wheat cultivars, the spikelet number per ear is remarkably constant and ranges from 18 to 22.

In most crops the first two spikelets above the collar are usually infertile. Water stress at the time of spikelet development can reduce spikelet number and spike size. In severe drought some spikelets, especially at the tip of the ear, abort giving rise to 'white tipped' ears which drastically reduce grain yield.

Number of grains per spikelet (Gr)

Potential grain number per spikelet is determined by the number of fertile florets per spikelet.

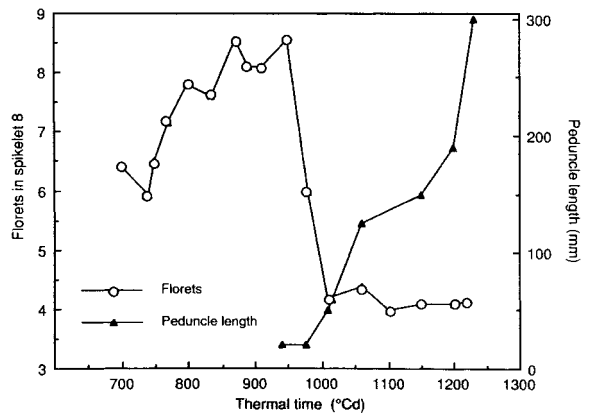
Floret formation starts just before spikelet initiation ceases, and the central spikelet of an ear can initiate up to 10 floret primordia. In a typical wheat crop, however, only 30 to 40% of the florets formed actually set grains.

After reaching a maximum, floret number is maintained for a short period, before the last florets to be formed lose turgidity and die. By anthesis floret number is stable, usually at 2 to 5 florets per spikelet. This is outlined in Figure 3.11.

Many florets may die when the flag leaf has fully emerged and the boot is visible. At this time, the ear and peduncle are growing most rapidly.

The exact causes of floret death are uncertain but the demands of the stem for dry matter may compete with the ear. It is possible that selecting wheats which partition less dry matter into the stem than the ear, at this stage, may increase the floret production, survival and grain number.

Figure 3.11



Formation and death of florets.

REPRODUCTIVE GROWTH AND GRAIN FILLING *(continued)*

A large number of ears per square metre, caused either by excessive seeding rates or high rates of nitrogen, is also associated with low floret survival. This occurs because photosynthesis per shoot is low, and therefore dry matter is in short supply.

Weight per grain (Wg)

The weight per grain – usually averaged – is determined by the photosynthetic capacity of the upper leaves, peduncle and ears; stem reserves and the storage capacity of each grain.

Soil moisture stress during anthesis and grain growth leads to fast leaf senescence, slow photosynthesis and often smaller grains.

Temperature has a large effect on the duration of grain filling. Lower temperature lengthens grain-fill duration, resulting in heavier grains. High temperature substantially reduces average grain weight, by shortening grain-fill duration.

Plant density does not seem to influence average grain weight significantly, but when soil moisture is deficient, grain weight may be reduced as soil moisture is depleted faster.

Relationship between yield components and grain yield

Grain weight is usually the most stable of the yield components, so crop yield is closely related to the number of grains that a crop produces.

Grain number is the product of the number of ears (E), the number of spikelets per ear (Sp), and the number of grains per spikelet (Gr); and these in turn are closely related to the crop biomass.

Yield component compensation

The yield components are determined sequentially during the development of the crop. Ear and spikelet number are set well before anthesis, grain number about anthesis, and grain size between anthesis and maturity. Thus the potential yields of a wheat crop can respond to improving or deteriorating conditions almost until maturity.

This flexibility is achieved by changes in the yield components. Low tiller numbers caused by stress during tiller formation may be compensated for by greater numbers of spikelets per ear and/or more grains per spikelet. Large numbers of ears per area from high seeding rates or excessive fertility may be compensated for by smaller ears, or light weight grains.

The mechanisms responsible for compensation originate in the interactions between crop and environment and between different organs within the plant. They are caused by competition for dry matter operating on the developmentally-flexible components of the plant.

Estimating grain yield from yield components

The yield of a wheat crop can be estimated by:

Grain yield (kg/ha) = Ears per square metre X Spikelets per ear X Grains per spikelet X Weight per grain (g) X 10 (see example below).

Ears per square metre

Count the ears in a square metre of crop, or count the number of ears in 1 metre length of row and multiply by 5.6 – there are 5.62 metres of row in one square metre for 7 inch or 17.8 cm row spacing. For 12 inch or 30cm spacing multiply by 3.3.

Spikelets per ear

Count the number on an average ear. For most crops it will be between 16 and 20.

Grains per spikelet

Count the grains in spikelets at the top, middle and bottom of the ear. More (and heavier) grains are usually set in the central spikelets. The number should be between 2 and 4, a conservative figure is 2 grains per spikelet.

Grain weight

The weight of an individual grain is impossible to estimate without a balance. Grain weights depend on growing conditions and on cultivar, but will be between 0.025 and 0.045 grams per grain. A good average figure is 0.036 g/grain, equivalent to 28 grains per gram.

Grain yield

Grain yield can therefore be calculated as the product of yield components:

$$\begin{aligned} \text{Yield} &= E/m^2 \times Sp \times Gr \times Wg \\ &= 100 \times (18 \times 2 \times 0.03) \\ &= 100 \times 1.08 \\ &= 108\ g/m^2 = 1{,}080\ kg/ha \end{aligned}$$

This leads to a simple rule of thumb, that a crop will yield about 1 t/ha for every 100 ears per square metre.

■ ENVIRONMENTAL CONTROL OF WHEAT GROWTH AND DEVELOPMENT

Wheat is grown commercially in a diverse range of environments, in both winter and summer, from the tropics to the edge of the arctic circle. The time from sowing to harvest can range from 60 to 330 days. Adaptation of wheat to these environments is achieved through genetic mechanisms governing plant response to temperature and daylength (photoperiod).

The interaction of the plant genetics with temperature and photoperiod determines the length of the life cycle and the cultivar's specific adaptation. Understanding these mechanisms and the factors controlling plant development is important in the generation of new cultivars and for crop management.

Temperature

Temperature is the fundamental environmental parameter that controls plant development. Increasing temperature can advance the timing of floral initiation and flowering (in calendar time) due to the general effect of temperature on the rate of biological processes. From about 0°C to 30°C most plant processes double in rate as the temperature increases every 10°C.

In some cultivars, development may not proceed or be delayed until seeds or plants have been exposed to a period of low temperature. This response is called vernalisation (from Latin *ver*, meaning "spring").

However, for many processes, such as leaf appearance, the rate at which the process occurs is constant in 'thermal time'. This concept is explained earlier in this chapter. Although temperature is the force driving plant development, photoperiod and vernalisation moderate its effect.

Photoperiod

The effect of the light duration each day, i.e. photoperiod, on plant development was first recognised in soybean and tobacco which flowered when the daylength to which they were exposed was artificially shortened. These are therefore termed "short day" plants.

This response contrasts to other plants. All of the temperate cereals develop and flower more rapidly when grown under long day lengths, and these are consequently known as 'long-day' plants.

The sensitivity to reduction in daylength (photoperiod) varies greatly among wheat cultivars. When a cultivar sensitive to photoperiod is exposed to short days it responds by forming more leaf primordia on its mainstem before initiating the ear.

Spear is a good example of photoperiod sensitivity. Sown in early summer, Spear will flower with only six leaves on the mainstem. But sown in the short days of May/June, Spear will form 10 or 11 leaves before flowering. A photoperiod insensitive cultivar will initiate the same mainstem leaf number regardless of sowing date.

Most photoperiod sensitive wheats respond to long days during vegetative development but can also respond during reproductive development and stem elongation. The effect of longer days on plant development can also vary greatly between cultivars. For some, a brief exposure to long days will initiate reproductive development, whilst other cultivars will need exposure to a longer photoperiod for a much longer time.

Vernalisation

A third mechanism modifying the development of plants to the environment is the requirement for exposure to cold before development can proceed. This is known as 'vernalisation.'

Temperatures for vernalisation to affect development are between 1 and 10°C. In cultivars with a vernalisation requirement, the shoot apex will remain vegetative, producing leaf primordia only, until the cold requirement has been satisfied. Plant development can continue if this cold requirement is only partially satisfied, but development will still be delayed.

Vegetative plants that require vernalization tend to have a prostrate growth habit. In the northern hemisphere winter, this helps to protect the young plant by keeping it beneath the snow.

Winter wheat cultivars are generally those with a strong response to vernalisation. They require a long period of exposure to the vernalising temperatures before their cold requirement is satisfied and the shoot apex advances to reproductive development and initiates floral primordia.

The vernalisation requirement for wheat varies greatly between cultivars and in a quantitative manner. Four major genes have been identified and many with minor effects.

Basic vegetative period

Phenological differences between wheat cultivars are normally attributed to differences in response to photoperiod and vernalisation. The inference, is that all cultivars would flower at about the same time, if these effects were removed by growing vernalised plants under long days. However, this is not the case.

The magnitude of variation amongst cultivars in the absence of photoperiod and vernalisation effects can be as great as that attributable to photoperiod and vernalisation. This trait is known as the basic vegetative period (BVP) and describes the minimum time taken by the plant to complete its life cycle.

BVP is strongly correlated with the duration of vegetative growth and therefore mainstem leaf number. In fact, leaf number can be used as a surrogate measure of BVP and can vary from 6 in Spear to as many as 18 in winter wheats such as Demeter. There is a tendency in cultivars with a long BVP, and large minimum leaf number, for leaves to emerge more slowly.

ENVIRONMENTAL CONTROL OF WHEAT GROWTH AND DEVELOPMENT *(continued)*

BVP is the basis for the rate of development of a cultivar, and it is the building block on which a development response is built. The addition of genes for sensitivity to photoperiod and vernalisation will slow this inherent rate of development. The mix of BVP with photoperiod and vernalisation can therefore be combined by plant breeders to tailor a cultivar to specific regions or sowing dates.

Cultivar adaptation

In Western Australia the beginning and end of the growing season are determined by the prevailing weather and are not influenced to a great extent by genotype or management. The plant life cycle has to be completed within these two constraints. The major consideration of the plant life cycle is the time of flowering in relation to the length of the growing season. It marks the change in plant development from the production of biomass and yield bearing structures to the formation and filling of grain.

Measurement of cultivar adaptation

Adaptation in wheat is characterised by response to vernalisation and photoperiod and measured by the time to flowering. Response to photoperiod is usually based on the difference between duration under natural (short daylength) and an extended photoperiod of (vernalised) plants grown in the field from a June 30 planting.

Vernalisation response can be measured as the difference between duration of vernalised (grown for 4 weeks at a mean temperature of 4°C prior to transplant to the field) and non-vernalised plants grown in the field over summer with an 18h photoperiod. BVP can be measured as the time to flowering for vernalised plants grown under long photoperiod.

The above approaches are a rudimentary method of classifying cultivars, and they also help to explain broad differences in why cultivars are adapted to particular climates.

European winter wheats are very sensitive to photoperiod and vernalisation and can possess long BVP, allowing them to be planted in the autumn, survive over winter, then proceed to flower in the spring. European spring wheats lack the vernalisation responsiveness of the winter wheats but still possess long BVP and/or a high sensitivity to photoperiod.

Most Australian wheats have a short BVP, little or very low sensitivity to vernalisation, but a wide range in sensitivity to photoperiod that can approach that of some European cultivars. It can be inferred that photoperiod is a more common determinant of adaptation than vernalisation in Australian wheats.

The above relationships explain why wheats from Northern Europe and the United States do not yield well in south-western Australia. When grown here, northern hemisphere winter wheats are very late flowering because our winter temperatures are not cold enough to quickly satisfy the high vernalisation requirement. European spring wheats are also late flowering when grown in southern Australia because photoperiod is shorter here (at 28 to 40°S latitude) than in northern Europe (at 40 to 50°N latitude).

Development in Australian cultivars

It was stated earlier that the greater variation to photoperiod amongst Australian cultivars suggests it is more common than vernalisation in determining differences in development patterns of Australian spring wheats.

Photoperiod is a more consistent environmental parameter than temperature, and it would be expected that photoperiod sensitivity should therefore be a more reliable predictor of flowering than vernalisation and thus impart wider adaptation. This is the case for the historical wheats Bencubbin and Gamenya and more recently for Spear and Stiletto. Each of these cultivars respond much more strongly to photoperiod than to vernalisation.

However two more recent cultivars, Tammin and Cunderdin, have demonstrated good general adaptation yet only respond marginally to photoperiod. Many other wheats grown commercially in Western Australia possess moderate sensitivity to both photoperiod and vernalisation.

All wheats grown in Western Australia possess a BVP of about 750°Cd. It has been postulated that a short BVP has an additional effect on growth, allowing the plant to complete its life cycle before the onset of moisture and temperature stresses at the end of the growing season.

The responses for some common wheats grown in Western Australia are listed in Table 3.3 along with some northern hemisphere winter wheats. These examples illustrate the great flexibility in developmental patterns available in different wheat cultivars.

With increasing knowledge of the effects of photoperiod, vernalisation and BVP, more latitude is available to the breeder to select for those combinations that optimise timing of floral initiation and flowering. Breeders have exploited this variation to produce cultivars adapted to different locations, sowing dates and lengths of growing season.

It is by matching the life cycle of the cultivar to the length of the growing season that yield potential is maximised. This is taken up in Chapter 7 with the concept of the 'Flowering window'.

ENVIRONMENTAL CONTROL OF WHEAT GROWTH AND DEVELOPMENT *(continued)*

Table 3.3. – Summary of the developmental responses for some common WA and some northern hemisphere wheats. All measurements are in thermal time (ºCd) using a base temp of 0ºC (P. Carlton, unpublished).

Wheat cultivar	Basic Vegetative Period	Response to Vernalisation	Photoperiod
Australian wheats			
Amery	740	90	160
Aroona	680	20	280
Bencubbin	840	280	360
Cadoux	730	270	290
Carnamah	700	210	220
Cascades	720	150	190
Cunderdin	690	330	200
Gamenya	750	230	320
Janz	790	110	280
Machete	690	220	330
Perenjori	760	340	160
Spear	750	60	510
Stiletto	810	70	410
Stretton	800	160	220
Tammin	810	320	100
Northern hemisphere winter wheats			
Currawa	830	170	760
Demeter	1640	210	420
Marksman	990	250	770
N87L 210	940	2260	540
Pomurka	990	1070	140
Priboi	1130	1630	210
Suckert Sand's Dickko	1290	1550	710

CHAPTER FOUR

CROP WATER USE

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■ CROP WATER USE

David Tennant

In Western Australia rainfall is usually the sole source of water for crop production. Only water stored in the soil at sowing or rainfall during the growth of the crop is available.

Water uptake by plant roots depends on:

- The depth of the root system (which determines the water available for extraction in the soil profile);
- The root length present in each layer of the soil; and
- The resistance to movement of water within the root axes.

Water uptake should be greatest with a large and deep root system. However, there is evidence that many cultivated wheats produce a larger root system than is required for uptake of available water – presumably as a survival mechanism against severe drought, or damage to roots by pests and diseases such as take-all. Deeper rooting results in greater water use in deep soils that allow differences to develop. However, on many soils, rooting depth is limited by an impermeable B horizon (duplex soils), low pH (acidity), high pH (alkalinity), boron toxicity, salinity or maybe one or more other factors. Species and variety differences in root depth and water use on these soils reflect tolerances to the impeding condition. Where the limiting condition is physical (impermeable B horizon on duplex soils) or has uniform effect, there are little differences in species and variety rooting depths and water use.

Also, it is important to 'meter' water in the drier parts of the wheatbelt so that crops have adequate moisture after anthesis for grain filling. This requires the breeding of cultivars that flower early in the season. Another option is to breed for varieties with high resistance to water movement in root axes, to limit early water use and conserve water for use by the plant at later stages of growth. At present, this is not a feature in commercial varieties.

THE 'WATER BALANCE' OF A CROP

The 'water balance' of a crop accounts for the various sources of water available for growth and the pathways through which water is used in the production of grain. That is, how well the plant balances the gains and losses of water over the season.

The losses

Water is lost or used by run-off, drainage and evaporation from soil and plants.

- Run-off: water that does not infiltrate into the soil may be lost as run-off from the soil surface. It is not considered an important loss for most crops in Western Australia, but where it does occur, yield potential is reduced and erosion may occur.
- Drainage: water percolating below the rooting depth of the crop. Early in the season the wetting front in the soil may exceed the root depth, however roots continue to grow and typically catch up with the wetting front. The potential for drainage is much greater on coarse textured soils because of their low capacity to hold water.
- Soil evaporation: water that evaporates from the surface of soils. While the surface is moist, water may be lost at the same rate as from a water surface: 2 to 3 mm/day in winter and up to 10mm/day in summer. Most water is lost when the surface is cultivated and left bare whilst the crop is establishing a cover of leaves.
- Transpiration: water taken up by the roots and evaporated from the leaves. It is the only productive pathway of water loss. To increase yield it is essential to increase the amount of water transpired by a crop.

Ideally, crop dry matter production and yield should be assessed in terms of water transpired, but transpiration is not easily measured in the field. Crop water use is usually measured as evapotranspiration, which is the combination of evaporation (during crop growth) and transpiration.

The gains

Rainfall just before, and during the growing season is the main source of water for crops. Water stored in the soil at sowing is also available to the crop. This may be from immediate pre-season rainfall, from heavy summer rains, or from a previous season's rainfall, stored under a fallow.

Over a set period – typically the crop growing season – the supply of water to the crop from rainfall (R) and any soil water stored at planting (SW1), must be balanced by the losses: run-off (RO), drainage (D), and evapotranspiration (ET). If these losses do not balance the inputs, the water stored in the soil at the end of the period (SW2) will increase or decrease to compensate. Thus the water balance is:

$$R + SW1 = RO + D + ET + SW2$$

MEASURING WATER USE

Of the terms in the water balance equation, only rainfall is easily measured. Stored soil water can be measured by soil sampling and determining the water content by weighing, drying and weighing again. A range of instruments are also available to measure stored soil water. The neutron moisture meter is the most widely used. In recent years, new instruments have become available for intensive measurement of water use and stored soil water – Bowen Ration Apparatus to measure evapotranspiration (ET), and Time domain reflectometer (TDR) to measure profile water contents and therefore the sum of ET, D and RO. When the TDR and Bowen Ratio Apparatus are used in tandem, subtracting ET (Bowen Ratio Apparatus) from the sum of ET, DR and RO (TDR) gives a measure of DR and RO. When RO is known to be negligible, we have a measure of DR.

Run-off and drainage are particularly difficult to measure, even with complex instrumentation and to overcome this, most measurements of crop water use or evapotranspiration are made under conditions where run-off and drainage are negligible. This applies to most crops grown in the wheatbelt, so the balance becomes:

$$ET = R + SW1 - SW2$$

Stored soil water at planting includes water stored from summer and pre-sowing growing season rainfall, and may be substantial on fine textured soils. No simple rule can determine the amount of rainfall stored at sowing because the pattern, amount and timing relative to sowing will determine losses from evaporation and summer pasture or weed use. As an example, only 25 to 30% of fallow water remains for the following crop.

Plant-available water

Plant-available water is water stored between 'wilting point' and 'field capacity'. It represents the soil's capacity to temporarily store water and then release it to the plant, and is important in determining the productivity of soil types.

Wilting point is the lower limit of plant available water, and as its name implies, is the point at which the plant is unable to extract more water and wilts. Some water remains in the soil below wilting point, bound tightly to the soil particles. The amount of water remaining at wilting point depends on the soil texture and varies from 2 to 3% on coarse sands to 20 to 25% on clays.

Field capacity is the upper limit and represents water left in the soil after all excess water has drained away after wetting up. It varies with soil texture and approximates about 12% for coarse textured sand-plain soils, but may be over 30% for clay soils. Water content is frequently above field capacity in some parts of the soil profile in the wetter months of the growing season. In extreme situations this leads to waterlogging. At other times, the plant can use some of this water as it drains down the profile.

Because of the almost metre to metre variability in soil texture, only a general guide to plant-available water content is possible. Examples of these estimates are given in Table 4.1.

Wettest and driest profiles

More practical estimates of available water in the field are obtained by difference from the driest recorded soil water contents down the profile. Except after late season rains, soil water contents down the soil profile near harvest describe the lower limit of water extraction by a crop. In these 'dry' soil water profiles, soil water contents near the surface, are below wilting point, due to water loss through evaporation (usually to around 30 cm but sometimes to 50 cm). Water contents below these depths are at first, at or near wilting point in the upper half of the profile, and then, increasingly higher than wilting point down to the final depth of water extraction, as root densities and capacities to extract water decrease. Wettest soil water contents are usually experienced sometime towards the end of July. Depending on the time of measurement, these can be above field capacity in the upper half of the profile, and tend to be lower than field capacity in the lower half of the profile, if water has not infiltrated to maximum depths of measurement. If measurements are made to well beyond maximum root depths, the two profiles

Table 4.1 – Effect of soil type on the amount of plant-available water (Estimates based on field and laboratory measurements)

Soil type		Available water (mm/100 mm depth of soil)	Storage to 1 metre (mm)
Poor white sand		1.5 to 4	15 to 40
Coarse yellow and grey sands		4 to 7	40 to 70
Loamy sands		5 to 9	50 to 90
Sandy loam (Avon valley)		10 to 15	100 to 150
Merredin sandy loam	: surface (0 to 20 cm)	15 to 18	30 to 36+
	: subsoil (20 to 80 cm)	18 to 25	144 to 200+

+ Add to give storage to 1 m.

■ MEASURING WATER USE *(continued)*

tend to come together at depth. Differences between the 'wettest 'and 'driest' soil water profiles provide estimates of water extraction from the soil by the crop. Figure 4.1 illustrates wettest and driest profiles measured under wheat crops on three soils at Merredin.

Crop water use

Water use of a range of wheat cultivars and one barley cultivar was studied at Merredin in 1987. The experiment was sown on May 27 and included old and modern wheat cultivars. Growth and water use were measured through the season, and the results are shown in Table 4.2.

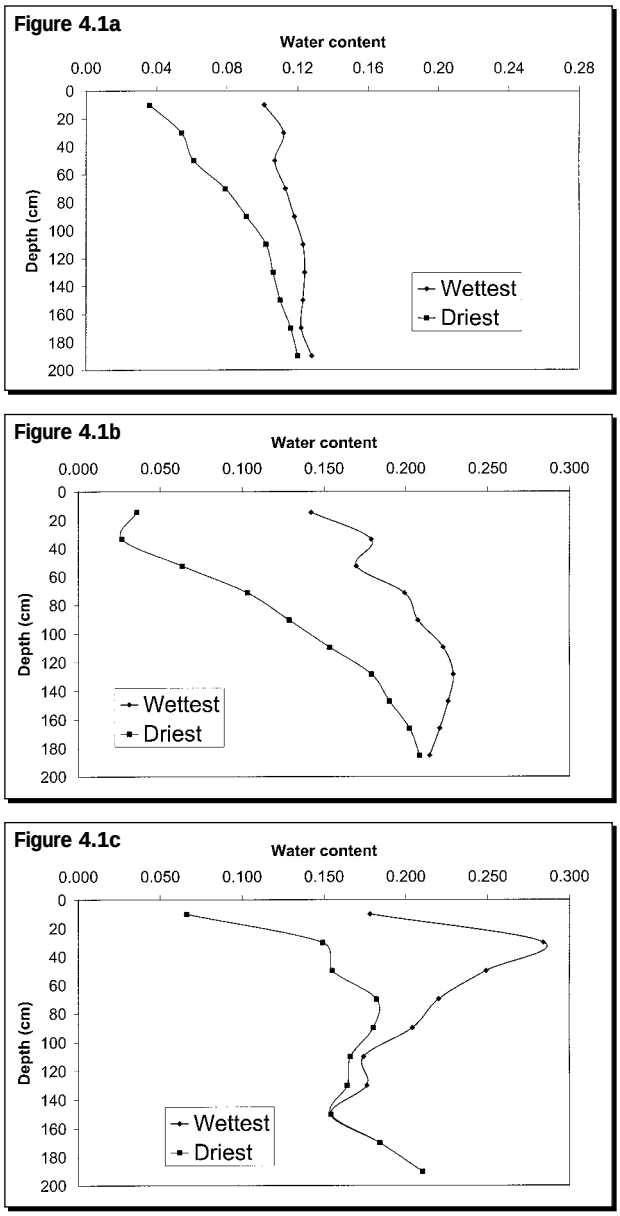
Purple Straw was a wheat cultivar of European origin grown in Australia in the late 1800s. Successively more recent cultivars mature earlier and yield more. Total water use was actually slightly less in the modern cultivars because the later-maturing cultivars were able to extract a little more water from deeper in the profile and there was some late rain.

What has changed between the old and modern cultivars is the partition of water use between the pre- and post-anthesis phases of the crop cycle. Older cultivars, basically because they take longer to flower, use almost all the water before flowering while modern, early flowering cultivars use more of the water supply after flowering.

Optimum grain production seems to be obtained at a ratio of pre- to post-anthesis water use of 2:1. In the experiment at Merredin the ratio was often less than 3:1, that is, post-anthesis water use was often less than 25% of total water use.

Evaporation from bare soil before the crop emerges, and before full canopy cover is established, is an important source of water loss. Cool winter conditions mean canopy development is slow and the soil surface is often wetted by frequent, but small, periods of rain. For the cultivars in Table 4.2, estimated soil evaporation was about 80mm or 40% of total water use.

Other work has estimated soil evaporation to be 63mm and 134mm for crops at Merredin and Wongan Hills equivalent to 38 and 44% of total water use.



Soil water profiles for wheat crops grown on a yellow earthy sand (sandplain), loamy sand over clay (medium) and red-brown earth (heavy land) at Merredin.

Table 4.2 – Yield and water use (mm) of old and new wheat cultivars and one barley cultivar (O'Connor) grown at Merredin in 1987.

Cultivar	Yield (kg/ha)	Days to flower	Water use (mm) Pre-flower	Post-flower	Total	Ratio Pre/post Flower
Purple Straw	1160	125	174	34	206	5.2
Bencubbin	1620	114	157	39	196	4.1
Gamenya	1680	109	147	39	186	3.8
Halberd	1740	113	156	40	196	3.9
Gutha	1890	103	140	46	186	3.0
Eradu	1830	106	146	40	186	3.7
Kulin	1890	106	145	40	185	3.5
O'Connor	2120	102	145	40	185	3.6

WATER USE EFFICIENCY

Grain yield can be considered as the product of the water used by the crop (WU) and a water use efficiency (WUE) expressed as yield per unit of water use (eg. kg/ha/mm). That is:

$$\text{Yield} = \text{WU} \times \text{WUE}$$

And

$$\text{WUE} = \text{Yield} / \text{WU}$$

Water use, also known as evapotranspiration (Et) has two components – water evaporated from the soil (Es) and water transpired (T) through the crop. To better understand WUE, we need to

(i) replace the WU term in this equation with Es and T,

$$\text{WUE} = \text{Yield} / (\text{Es} + \text{T})$$

(ii) divide the top and bottom of the right hand side of this equation by T,

$$\text{WUE} = \frac{\text{Yield} / \text{T}}{1 + \text{Es} / \text{T}}$$

(iii) recognise that water loss from the soil can also include run-off (R) and deep drainage (D).

$$\text{WUE} = \frac{\text{Yield} / \text{T}}{1 + (\text{Es} + \text{R} + \text{D}) / \text{T}}$$

In this equation, Yield / T is the transpiration efficiency (TE) of the crop. A measure of T is needed to arrive at a value for TE. T is usually calculated by subtracting Es, R and D, from WU. Es, R and D are difficult to measure, thus T and TE are not often calculated. The alternative (some would say compromise) is to use WU and WUE. When doing this, it is important we understand that WUE is calculated using a water use value that in addition to T also includes Es, and in many situations R and D as well. Failure to understand this has led to many misunderstandings when using applications based on WUE.

The structure of the final equation suggests options for improving water use efficiency.

- Increasing TE, or yield produced per unit of water transpired will increase WUE. TE can be improved by increasing the proportion of vegetative growth during the cooler winter months. This can result in higher dry matter production and yield if variety choice and other conditions are suitable. The higher yields achieved from early sowing are a consequence of this. TE is also determined by the physiology of the plant. This aspect of TE is only improved by breeding.
- If water supply is limited, WUE can be improved by increasing T at the expense of one or more of Es, R and D. The strategy here is to increase productive water use and reduce non-productive water losses. For example, in restricted rainfall environments, better agronomy for faster early ground cover and higher dry matter production serves to reduce Es and increase T, to give higher yields. The sum of Es and T, or water use, may increase slightly, but not substantially.
- If water supply is increased, WUE will only be increased if T is increased proportionately more than the sum of Es, R and D.

Generally, all management options to improve yields and WUE aim at increasing the proportion of water transpired by the crop.

Measurement of water use efficiency

In the field, we can measure water use by measuring the change in stored soil water between sowing and harvest and adding rainfall received over this period. WUE is then calculated by dividing yield by water use. Table 4.3 summarises some measurements of yield, water use and water use efficiency of wheat at a number of locations in Western Australia. The average is 8.6 kg/ha/mm and the values range from 5.6 to 13.6 kg/ha/mm. Similar values are reported from eastern Australia and overseas. Lowest values in the table occur on free draining sands where water is lost below the root zone, with low fertility treatments where little dry matter is produced and with older lower yielding wheat varieties.

An alternative approach

To calculate the WUE of farm yields, the yield can be divided by the growing season rainfall. This 'rain use efficiency' index usually has a value of about 10 kg/ha/mm in the central and eastern wheatbelt of Western Australia, and has been used as a target or benchmark against which the efficiency of a crop enterprise can be measured.

WATER USE EFFICIENCY *(continued)*

Table 4.3 – Results of crop water use studies, 1979 to 1992.

Year	Location	Cultivar	Grain Yield (kg/ha)	Crop Water Use (mm)	Water use Efficiency (kg/ha/mm)
1979	Wongan Hills	Gamenya	1,609	212	7.6
	Avondale	Gamenya	2,441	237	10.3
	Merredin	Gamenya	1,647	196	8.4
1980	Wongan hills	Gamenya	1,203	181	6.6
	Avondale	Gamenya	1,429	178	8.0
1981	Wongan Hills	Gamenya	2,098	290	7.2
1982	Wongan Hills	Gamenya	1,982	256	7.7
1983	Wongan Hills	Gamenya	3,228	299	10.8
			2,613	270	7.7
1984	Merredin	Gutha			
	Red-brown earth		1,873	165	11.4
	Duplex soil		2,131	223	9.6
	Acid sand		1,299	177	7.3
1985	Merredin	Gutha			
	Wheat/wheat – N		1,320	168	7.9
	Wheat/wheat +N		1,770	171	10.4
	Lupin/wheat – N		1,860	186	10.0
	Lupin/wheat + N		1,730	181	9.6
1987	Merredin	Purple Straw	1,162	206	5.6
		Gamenya	1,674	186	9.0
		Kulin	1,892	187	10.1
1988	Merredin	Purple Straw	1,360	230	5.9
		Gamenya	2,415	239	10.1
		Kulin	3,006	221	13.6
	East Beverley	Gutha	1,980	255	7.8
1992	Merredin	Gamenya	1870	290	6.7
		Kulin	2660	292	9.1
		Spear	1830	298	6.2
	Mullewa	Gamenya	2040	234	8.7
		Kulin	1840	210	8.7
		Spear	1810	236	7.7

The Two Tonne Clubs established in 1979 tested this 10 kg/ha/mm target by deciding to eliminate all constraints other than water supply on grain production.

They aimed to grow a disease-free, weed-free, well fertilized, early sown crop of a recommended variety on the best cropping land on each farm. A quarter of the crops grown this way achieved the target of 10 kg/ha/mm and nearly half reached 9 kg/ha/mm or better.

In the mid 80s, this idea for using growing season rainfall as an estimate of crop water use and a target WUE was expanded to include the water-limited yield potential of a crop and better seasonal estimates of water use and WUE.

■ ESTIMATING CROP YIELD POTENTIAL

The concept

The practice of using yield potential estimates as benchmark values for assessing the success of cropping came out of an extensive study of yield variability and its causes in wheat in South Australia. Yield and water use data were collected at 62 sites over a period of 12 years (1964-75). When these yields were plotted against the measured values of water use, the data points were widely scattered and yields were poorly correlated with water use (Figure 4.2). To interpret this scatter, a line was drawn through the highest yields at different levels of water use. This line was seen to define a linear relationship between yield potential (maximum achievable yield) and water use. The spread of data points below this line were thought to represent sites where yields were limited by factors other than water supply – extremes of temperature, agronomic deficiencies, pests, diseases, unsuitable soil physical conditions and waterlogging.

The yield potential line in this data set intercepted the water use axis at 110 mm and had a slope of 20 kg/ha/mm. The implications arising were:

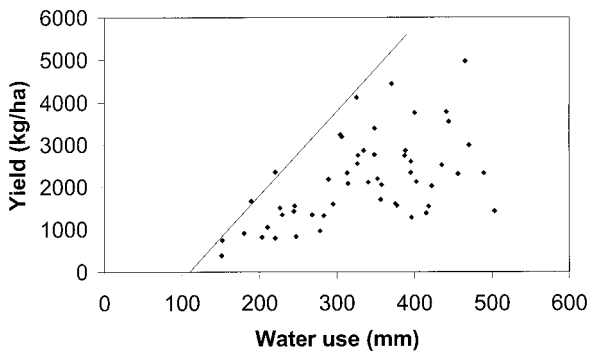
- On average, in South Australia, up to 110 mm of water (stored water and rainfall) is lost through soil evaporation, and is not used for grain production.
- Water in excess of this 110 mm contributes to a water-limited yield potential, to the extent of 20 kg/ha/mm.

These 'water loss' and 'water use efficiency' values were included in what is known as the 'French and Schultz equation', named after the developers of the yield potential concept.

Yield potential = (Crop water use – 110) x 20

The parameters in this equation are thought of as being constants. While this is for the most part true for the 'water use efficiency' term, the 'water loss' value of 110 mm varies with management, rainfall and soil type. Though largely made up of soil evaporation, it can also include run off and deep drainage. On hard setting soils in South Australia, water loss included run off and on average totals 170 mm.

Figure 4.2



Yield and water use data used to generate the 'French and Schultz' equation for wheat.

In contrast, in low rainfall conditions and under crops grown in Queensland on stored soil water, average water loss was of the order 75 mm and 45 mm respectively. In similar data derived in Western Australia, water loss was of the order of 130 mm on deep sand at Wongan Hills, compared to 110 mm on sandy loam and red duplex soils at Avondale and Merredin. The difference was thought to be due to drainage (20 mm average) at Wongan Hills. In overseas data, soil evaporation under a well managed crop has been estimated to be around 20% of crop water use, compared to 40% of crop water use under an average crop. Published values of soil evaporation under a crop range from 20% to 60% of total water use.

While run off and drainage can this way impact on the 'water loss' value, the 'French and Schultz' equation is in effect a simple procedure to partition water use into its components of transpiration and soil evaporation. In reality this is a more complex process. However, the relationship between yield and water use as defined in Figure 4.2 is the best available method of estimating the water-limited yield potential of a crop. This is because it attempts to isolate and subtract water lost through non-productive evaporation, and to use a measure of the efficiency of conversion of productive transpiration to grain.

Some have argued that this measure should be around 16 kg/ha/mm, and not 20 kg/ha/mm. There are several local and overseas data sets available which support this view, but there are differences in the way the data are interpreted. The 16 kg/ha/mm value is usually obtained when a line is fitted to the data, to give an 'average' water use efficiency. This contrasts with the 'French and Schultz' approach of fitting a line through the highest yields, to give a 'potential' water use efficiency of 20 kg/ha/mm. The 'French and Schultz' equation enables the producer to set a target or benchmark water-limited yield potential to aim at. In this context, the issue is more one of using a consistent water use efficiency value than any decision on choice.

Comparison of yields achieved with a calculated yield potential may indicate that some property or management practice is severely constraining yields. Alternatively, a simple transposition of the 'French and Schultz' equation enables the producer to calculate water use efficiency achieved by a crop, and then compare it against a target or potential water use efficiency, to achieve the same end.

WUE = Yield / (Crop water use – 110)

Being opposite sides of the same equation, the ratio of yield to yield potential is the same as the ratio of water use efficiency to potential water use efficiency.

The two steps required to estimate water-limited yield potential or water use efficiency achieved are to:

- Estimate water use from growing season rainfall; and
- Use the 'French and Schultz' equation to calculate yield potential or water use efficiency achieved.

■ ESTIMATING CROP YIELD POTENTIAL *(continued)*

Estimating water use from growing season rainfall

Crops in southern Australia are grown for the most part on growing season rainfall. Simple equations can be derived to show a near one to one relationship between water use and growing season rainfall. One developed for South Australia is:

Water use (mm) = -18.4 + 1.04
(April to October rainfall, mm)

A simpler approach is to use growing season rainfall as an estimate of water use. Estimates made this way will need to allow for:

- Significant summer rainfall that adds to soil water storage and increases water available for use above growing season rainfall.
- Run-off and deep drainage (depending on site) that decreases the amount of water available for use below growing season rainfall.

Stored soil water (SSW) from summer rainfall can be estimated as a percentage of rainfall received over summer. The different procedures used include:

- SSW = 30% Summer rainfall
  or
- SSW = 25% of January and February rainfall + 50% of March rainfall

With each of these, only consider significant rainfall events (say >15 mm). A better estimate of stored soil water is possible by using PYCAL; a model that accounts for water loss from soil evaporation and then subtracts this loss from total rainfall received over summer, to give an estimate of stored soil water. As yet, no simple procedure is available to estimate water loss through run-off and deep drainage. It is important that these losses be considered when evaluating the yield potential and water use efficiency values derived from using the 'French and Schultz' equation.

Setting yield potential

While the 'French and Schultz' equation is now widely used in extension activities aimed at improving productivity, there has been ongoing controversy on whether the benchmark yield potential or water use efficiency should be one that was achievable, rather than a distant target. Most extension activities now lean towards using an achievable target rather than a potential target. This is done by using a target water use efficiency set at 75% of the generally accepted potential water use efficiency. Thus the 'French and Schultz' equation to calculate yield potential for wheat becomes:

Yield potential =
(Crop water use – 110) x 15

And, water use efficiency is calculated as:

WUE =
Yield / (Crop water use – 110)

Table 4.4 lists outcomes from these calculations done using rainfall data for Mingenew and average yields for the Shire of Mingenew over the period 1976 – 1996. Stored water at April 1 was estimated using PYCAL. The 'Ratio' can be yield/yield potential or water use efficiency/ target water use, and can be expressed as a percentage. Analysis of the yield data in Table 4.4 shows an average yield increase of 65.6 kg/ha/year, the highest of any shire in the wheatbelt of Western Australia over the period 1980 to 1994.

Because growing season rainfall is the main determinant of crop water use, yield potential will vary with season and the benchmark or target yield potential has to be calculated each year. However, if the focus is on comparing water use efficiency achieved against a potential or target water use efficiency, this value is the same each year (20 kg/ha/mm or 15 kg/ha/mm). For strategic planning of farm enterprises, the most useful figure is the average yield potential or water use efficiency and the variation of yield potential or water use efficiency from season to season.

Table 4.4 shows how calculations are made at the end of the growing season, when growing season rainfall and yields are known. Yield potential forecasts can also be made as the season progresses, to support management decisions made. Table 4.5 shows one way of doing this, using average monthly rainfall totals and an estimate of stored soil water.

At the start of the growing season, the only information available is an estimate of stored soil water and average monthly rainfall totals. Yield potential is calculated using these values. By May, April rainfall is known and replaces average April rainfall in the estimate of crop water use and yield potential. In this example, lower than average April rainfall is reflected in a drop in the yield potential estimate. As the season progresses, monthly totals of rainfall received replace successive average monthly rainfall values. The yield potential forecast is updated, as each monthly rainfall total becomes available. PYCAL provides a procedure for doing these calculations on a daily basis.

Problems in estimating yield potential and water use efficiency

The French and Schultz equation is used here to summarise outcomes from a complex interactive process involving water availability and use, dry matter production and yield. The method used makes several assumptions:

- Water is the only factor determining grain yield.
- There is a near one to one relationship between growing season rainfall and water use.
- The relationship between water use and yield potential is consistent and widely relevant.

■ ESTIMATING CROP YIELD POTENTIAL *(continued)*

Table 4.4. Estimates of water use efficiency and yield potential for the Shire of Mingenew based on estimated crop water use, 110 mm of water loss and 15 kg/ha/mm potential water use efficiency.

Year	Stored water estimate (mm)	Growing season rainfall (mm)	Yield (kg/ha)	Calculated values: Crop water use (mm)	Yield potential (kg/ha)	Water use efficiency (kg/ha/mm)	Ratio
1980	0	268.4	1157	268.4	2376	7.3	0.49
1981	0	333.7	1061	333.7	3356	4.7	0.32
1982	0	249.3	899	249.3	2090	6.5	0.43
1983	0	312.7	805	312.7	3041	4.0	0.26
1984	41.3	363.0	1724	404.3	4414	5.9	0.39
1985	0.5	211.8	989	212.3	1534	9.7	0.64
1986	22.4	409.7	1406	432.1	4832	4.4	0.29
1987	1.6	239.2	1037	240.8	1963	7.9	0.53
1988	0	353.1	1634	353.1	3647	6.7	0.45
1989	0	265.6	1534	265.6	2334	9.9	0.66
1990	52.8	428.6	1744	481.4	5571	4.7	0.31
1991	76.5	276.6	1759	353.1	3647	7.2	0.48
1992	15.4	395.5	1752	410.9	4513	5.8	0.39
1993	0	331.4	2326	331.4	3321	10.5	0.70
1994	0	250.1	1975	250.1	2102	14.1	0.94
Lowest	0	211.8	805	212.3	1534	4.0	0.26
Average	14.0	312.6	1453	326.6	3249	7.3	0.52
Highest	76.5	428.6	2326	481.4	5571	14.1	0.94

Table 4.5 – Procedure to make yield potential forecasts as the season progresses. Bold values show information that is known.

Stored soil water (mm)	Growing season rainfall (mm)							Total	Crop water use (mm)	Yield potential forecast (kg/ha)
	Apr	May	Jun	Jul	Aug	Sep	Oct			
Information available at the start of the growing season										
40	23	41	54	53	38	26	19	254	294	2760
Information available May 1										
40	**12**	41	54	53	38	26	19	243	283	2595
Information available June 1										
40	**12**	**92**	54	53	38	26	19	294	334	3360
Information available July 1										
40	**12**	**92**	**58**	53	38	26	19	298	338	3420

■ ESTIMATING CROP YIELD POTENTIAL *(continued)*

Factors affecting grain yield

Many factors other than water also influence yield. The argument used is that water sets the upper limit for yield and that management is focussed on optimising conditions for growth, development and production. However, with wider application of this concept, it is soon evident that other factors set limits and give rise to alternative yield potentials.

Different soil types often occur within a single paddock and can differ greatly in yield even though growing season rainfall is the same. Fertility, structure, topography, sub-surface layers and depth of water penetration contribute to the variability. While management or agronomy can modify surface conditions, to give higher yields and water use efficiencies, soil conditions at depth can be difficult to manage and in the extreme be intractable. Thus, the yield potential on some soils can be significantly below the water limited yield potential.

Relationship between growing season rainfall and water use

Water available for plant growth is made up of stored soil water from summer rain and growing season rainfall. As growing season rainfall is the largest component of available water, there is a close relationship between growing season rainfall and crop water use. However, water supply is also a function of infiltration and distribution of growing season rainfall in the soil. Run off and deep drainage result in a net loss in available water that tends to increase as rainfall exceeds an optimum level, and waterlogging reduces the efficiency of conversion of water to dry matter production and yield. Also, depending on rotation, there is often water remaining in the soil after the previous crop or pasture, indicating lower water use than growing season rainfall. Access to this water in the following year often results in water use being higher than growing season rainfall in low rainfall years. Thus the relationship between growing season rainfall and water use can not only deviate from the expected 1:1 line but can also vary depending on soil type.

Remember also that it is generally assumed when using the 'French and Schultz' equation that the water loss value of 110 mm is the same in low and high rainfall years. This translates to an increasing proportion of productive to non-productive water use and increasing water use efficiencies as growing season rainfall and therefore estimated water use increases (see Table 4.6). The developers of this equation were aware of this problem at low levels of growing season rainfall (< 150 mm) and provided an alternative estimate of water loss for these years. PYCAL allows the user to calculate water loss as a fixed percentage of estimated water use. Reference to the data behind the 'French and Schultz' equation indicates that the average water loss of 110 mm equates to 1/3rd of average water use. In dry years, water loss was lower than in wet years.

Table 4.6 – Water use efficiency, calculated as yield/water use, varies with the level of water use.

Yield is calculated from the formula:

Yield = (Water use – 110) x 15

Water use (mm)	Yield (kg/ha)	Yield/water use (=WUE) (kg/ha/mm)
150	600	4.0
200	1350	6.8
250	2100	8.4
300	2850	9.5
350	3600	10.3

Universality of the 'French and Schultz' equation

When first used, many concerns were expressed as to whether a relationship established in South Australia would apply within Western Australia. The main concern was with the north-south variation in length of growing season and its impact on estimates of crop water use. Work done to investigate this showed that when allowance was made for length of growing season (April to September – north, April to October – central and April to November – south), the equation was robust and applied throughout.

Also, the data that gave rise to the 'French and Schultz' equation are not unique. Similar data sets are available in the literature for a wide range of environments. Analyses of these data sets show average water loss of the order of 100-110 mm and average water use efficiencies of the order of 16 kg/ha/mm. As indicated earlier, the 20 kg/ha/mm water use efficiency value in the 'French and Schultz' equation, describes the water use efficiency achieved by the highest yielding crops. It is instructive to know that even higher values are reported in the literature. To reiterate, the issue is more one of using a consistent target water use efficiency than one of 'correctness'. Note also the earlier concerns with using an apparently unachievable target water use efficiency of 20 kg/ha/mm. The compromise choice of 15 kg/ha/mm is now often exceeded with improved management.

These and other concerns with procedure used to estimate yield potential and water use efficiency relate to likely effects on the components of the 'French and Schultz' equation. These are addressed in the 'crop monitoring' programs included in applications that use the 'French and Schultz' equation. The aims are twofold. Firstly to learn about the processes involved in growth, development and production, and to develop benchmarks along the way. Secondly, to have information at hand to interpret differences between achieved and target yields and water use efficiencies. Then, should this information be inadequate, further steps can be taken to resolve the problem. It is important that the interpretive process can distinguish between issues that are manageable and those that are not. For example, on some soils, yields and water use efficiencies may never improve beyond say 50% of target values.

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CHAPTER FIVE

NUTRITION

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■ NUTRITION

For profitable grain production, wheat plants require both the macro-nutrient element's carbon, oxygen, hydrogen, nitrogen, phosphorus, sulphur, potassium, calcium, and magnesium, and the micro (minor)-nutrient elements, commonly called trace elements; copper, zinc, manganese, iron, molybdenum, boron and chloride. Cobalt is known to be required for legumes, but may also be required for wheat. All plants need water which is taken up by plant roots from the soil. Carbon is largely taken up by leaves from the atmosphere as carbon dioxide. Oxygen is also taken up by leaves from the atmosphere. Hydrogen is mostly derived from water taken up by plant roots from the soil. All the other nutrient elements are taken up by plant roots from the soil; the rest of this chapter considers these nutrient elements taken up from the soil.

The wheat plant combines nutrients absorbed through the roots with the carbohydrates made during photosynthesis to form new tissues. During photosynthesis, which largely takes place in leaves, plants use solar energy to convert carbon dioxide and water to complex organic molecules, which are carbohydrates; oxygen is a by-product which is returned to the atmosphere via the leaves. Further reactions in the plant use the carbohydrates to: (1) obtain energy for growth and development, a process called respiration, involving oxygen taken up by leaves from the atmosphere; carbon dioxide is a by – product returned to the atmosphere via the leaves; (2) form amino acids and proteins by combining the carbohydrates with nitrogen taken up from the soil.

Plant roots have evolved to take up water and nutrient elements from the soil; leaves have evolved to take up and return carbon dioxide and oxygen to the atmosphere, and to return water vapour, derived from the water taken up by the plant roots from the soil, to the atmosphere. Consequently, except for carbon dioxide and oxygen, uptake of nutrient elements from leaves is usually minor. However, copper, zinc, manganese and molybdenum, which are minor nutrients required in much smaller amounts and which can improve profitable grain yields if taken up by plants before flowering, can be sprayed onto wheat crops to be taken up by the leaves. This is usually only done if tissue tests of crops, measured using tissue samples collected before flowering, indicate deficiency may reduce grain production at the end of that growing season. The crops are sprayed because in the case of these elements profitable grain yield increases can be obtained if deficient crops are sprayed before flowering and grain formation. Spraying will be discussed later when each of these elements is considered in more detail.

For the nutrient elements taken up by the soil, the 'law of the minimum': 'the yield of the plant is limited by a deficiency of any one essential nutrient, even though all others are in adequate supply', first proposed by von Leibig in about 1862, was a major step in helping to understand the effects of these nutrients on plant growth and the need for fertiliser applications.

Roots take up (absorb) nutrients from the soil solution. That is, all the nutrient elements taken from the soil are absorbed in a water-soluble form by roots. Therefore, the concentration of nutrients in the soil solution determines the rate of uptake.

Uptake of nutrient elements from the soil and into plants depends on:

- the availability of the nutrient in the soil;
- movement of the nutrient, in soil solution or along the surfaces of soil constituents, to the root surface;
- growth of roots through the soil thereby intercepting nutrient elements released to solution from soil constituents or from soil organic matter;
- uptake of nutrient into the root; and
- translocation of nutrients from root to shoot, leaves, flowers and grain.

Uptake mechanisms

Mass flow

During the day, when the plant is turgid and has access to soil water, plants transpire water. In this process, water is evaporated from leaves when structures in the leaves called stomata are open. The stomata are usually closed during the night, or during the day when the plants are not turgid because they cannot get sufficient water from dry soil. When the plants are transpiring, water is drawn all the way from the soil to the leaves to replace the water evaporated to the atmosphere. The water is dragged in a continuous stream from the soil to plant roots and then through the water – conducting vessels in plants (xylem) to the evaporating surfaces in the leaves. This stream of water is called the transpiration stream or mass flow, and it is initiated and driven by transpiration of water through the open stomata in the leaves.

Nutrient elements that are soluble and so mobile in soil solution are largely transported through the soil to plant roots by mass flow. Therefore, the supply of soluble and mobile nutrients such as nitrate, calcium, magnesium and sulphate, to the root surface in moist soils is largely by mass flow.

Diffusion / concentration gradient

Less soil-mobile nutrients (potassium) move to plant roots along a concentration gradient by a process called diffusion. Concentrations of these elements are usually lower at root surfaces as roots absorb the nutrients from solution and so the concentration of the elements is smallest near the portion of the roots where uptake into the plant is occurring, and is greater away from the plant roots. Because there is more of the element away from the root, most of the elements will move to the root. Therefore, the net flow of the element in soil solution is from high to low concentration and so toward the root, hence the term concentration gradient.

NUTRITION *(continued)*

Root interception

For very insoluble nutrients that have very low concentrations in soil solution (phosphorus, copper, zinc), movement to roots by mass flow and diffusion is too slow. Plant roots obtain these elements by growing through the soil and so intercepting zones of soil with reasonable quantities of the elements in solution that are in equilibrium with insoluble forms of the elements very close by in the soil. As the plant roots absorb the soluble forms of these very insoluble elements from solution, more of the element dissociates or dissolves from the insoluble forms in the soil very close by the root to replenish the soluble form of the element taken up by plant roots. All insoluble forms of all elements will dissolve to a certain extent to maintain a concentration of the element in solution, as determined by the solubility of the compounds involved. In addition, nutrient elements returned to the soil as organic matter are food for a host of soil organisms (soil animals, fungi, bacteria, algae, protozoa). These organisms process the organic matter, changing it physically and chemically, to eventually return nutrient elements to soil solution where they can be taken up by plant roots.

Factors affecting uptake

Plant roots take up nutrient elements from soil solution selectively, and accumulate them at a higher concentration within the plant than in the soil solution. This requires energy which is derived by respiration using carbohydrates made during photosynthesis.

Soil and environmental stresses that either limit the energy available for uptake (low solar radiation, due to cloud cover and lower solar radiation from the sun during mid winter compared with autumn and spring; low temperatures in mid winter; and waterlogging) or reduce the availability of the nutrient at the root surface (dry soil, compaction, low fertiliser supply, reduced root growth due to aluminium toxicity caused by soil acidification, or pruning of roots by pests,diseases and hebicides), will therefore restrict the uptake of nutrients and reduce the growth of the plant.

Topics considered in the Chapter

This chapter looks at those chemical features of Western Australian soils which affect nutrient supply and examines the nutrients of greatest importance to a wheat crop in these soils: phosphorus, nitrogen, sulphur, potassium, copper, zinc, manganese, molybdenum. No yield responses of wheat have been measured in Western Australia to applications of fertiliser calcium, magnesium, iron, boron or cobalt, so these elements are not considered further in this chapter. Boron toxicity is a problem for wheat in some alkaline, saline soils in low rainfall areas of Western Australia, so boron toxicity is discussed. Soil acidification, and ways to minimise its effects on reducing grain yields of wheat are also considered.

■ IMPORTANT CHEMICAL PROPERTIES OF WHEAT GROWING SOILS IN WESTERN AUSTRALIA

M.D.A. Bolland and J.W. Bowden

It is the chemical properties of soils that affect nutrient availability. The materials that constitute the soil determine the chemical properties.

Constituents of the soil

The soil components are either inorganic or organic.

Inorganic components

All the mineral constituents of soils are originally derived from igneous rocks which were formed by the solidification of molten magma. Silicon, oxygen, aluminium, iron, calcium, sodium, potassium and magnesium compose 98% of igneous rocks. Other elements (including phosphorus and minor elements) make up the remainder. As the magma cools and forms rocks, minerals begin to form and crystallise. Different types of minerals will form depending on the relative mix of elements in the magma and the conditions under which it cools. The type of minerals that are formed will largely determine the type of soil formed.

Other processes, including geological pressures and reformations, and the extent of weathering of rocks by the climate (temperature, rain and wind), are also important in the formation of particular soils. Two other types of rocks are formed from igneous rocks. These are metamorphic and sedementary rocks. Igneous rocks can be subject to pressures as the surface of the earth is bent and twisted to form mountains and valleys. In the process the igneous rocks are altered to form metamorphic rocks. In addition, material from both the igneous and metamorphic rocks are eroded by wind and/or water to another location and the redeposited material forms sedementary rocks.

Soils are formed from igneous, metamorphic and sedementary rocks as a result of changes to the rocks exposed at the earth's surface caused by weather (temperature, wind, rainfall), and eventualy by organisms and plants growing in and on the soils.

The mineral components of a soil are present as sand, silt, clay, together with crystalline (structured) and amorphous (not structured) oxides. Amorphous oxides are chemical compounds arranged in a disorganised manner; they are like a solidified jelly rather than the crystalline structures of sand, silt, clay and crystalline oxides. The particle size ranges from 50 µm and 2 mm for sand, 2 µm to 50 µm for silt and less than 2 µm for clay. The size of the crystalline and amorphous oxides range from smaller than a clay particle to larger than a sand particle. Oxides of iron and aluminium, often called sesquioxides, are the most important in most Western Australian soils used to grow wheat. These oxides exist as discrete particles, as well as coatings on the sand, silt and clay particles. Ironstone gravels are a conglomeration of iron and aluminium oxides and have low surface areas. The iron oxides are largely responsible for the yellow, red and brown colours of soils, colouring sand, clay and silt particles. The iron and aluminium oxides can act as cements to bind other soil particles together, and play a major role in adsorption of nutrient elements, particularly phosphorus, sulphur, copper, zinc, manganese and molybdenum.

The major clay in most Western Australian soils is kaolinite, comprising an aluminium oxide joined to a silicon oxide (an alumina octahedral layer (gibbsite) is joined to a silica tetrahedral layer). Several of these bilayer structures are joined to form stacks, that are the basic structure of the clay. In its pure form, kaolinite is white in colour; very pure white deposits of kaolinite occur naturally in Western Australia, such as near the town of Greenbushes in the south west. However, most natural kaolinite in Western Australian soils is stained yellow, brown and red due to the presence of iron (responsible for the colour) and aluminium oxides, as coatings or as discrete particles.

Organic matter, usually present near the soil surface, is largely responsible for brown and black to grey colours in soils.

The surfaces of many of the inorganic soil constituents posseses both positive and negative charge sites. This is paricularly so for the clays and oxides. Most nutrient elements exist in soil solution as charged species, called ions, which can balance, and so neutralise, the surface charges. The positive ions are called cations, and the negative ions are called anions. In this way, the nutrient elements are retained by the surfaces of the inorganic soil constituents, and the soil is said to have a cation (positive ions retained) or anion (negative ions retained) exchange capacity. The word exchange is used because the ions that balance the surface charge can be replaced by other ions of the same charge. For example, positive calcium ions (cations) balancing the negative surface charge sites can be replaced by potassium or ammonium cations. In addition, many ions and molecules that exist in the soil solution, including some nutrient elements, chemically react with other ions or molecules in soil solution to form insoluble compounds that precipitate out of solution as the solubility product of the compounds involved are exceeded. This process is called precipitation. Alternatively, many ions and molecules in the soil solution chemically react with chemically unstable, and so chemically reactive ions and molecules exposed at the surfaces of the inorganic soil constituents to form more stable, insoluble compounds at the surface. This process is called adsorption. Chemicals (ions and molecules) can be adsorbed by soil surfaces that have no electrical charge or have a charge of the same sign as the chemical in question or have an opposite charge. In addition to cation or anion exchange capacities of soils, adsorption is another way nutrient elements in soil solution can be retained by inorganic soil constituents. Precipitation and adsorption are similar reactions that occur at the same time, but adsorption occurs at a solid surface. In practise it is difficult to differentiate between

IMPORTANT CHEMICAL PROPERTIES OF WHEAT GROWING SOILS IN WESTERN AUSTRALIA *(continued)*

precipitation and adsorption reactions, so both reactions are collectively called sorption, and both are therefore considered as ways nutrient elements are retained by soils.

The clay fraction and the crystalline and amorphous oxides have the largest impact on both the chemical and physical properties of the soil. This is because these particles have a very large surface area to volume ratio. A small percentage of, for example, clay in the soil represents a large surface area. Many of the chemical processes in the soil involve interaction with the surfaces of clay particles and also the smaller crystalline and amorphous oxides.

Organic components

When fresh organic materials are added to a soil they are decomposed by soil organisms to ultimately form carbon dioxide and simple inorganic salts. This is because soil organic matter is a source of food for many of these soil organisms, including earthworms, soil insects, fungi, algae, bacteria and protozoa. Some of these physically break up the organic matter to smaller components; others both physically and chemically alter it. In the process, nutrient elements are released from the organic matter to soil solution, a process called mineralisation, and so can be taken up by plant roots. However, the soil organisms need nutrient elements to live, and so remove some elements from soil solution and from the organic matter they are processing and incorporate them into their bodies. Most of these elements end up as soil organic matter. In this case the nutrient elements are rendered unavailable to plants, a process called immobilisation.

Complete decomposition of soil organic matter is a complex process that proceeds over a long time. Some materials are quickly broken down (such as plant sugars and proteins) while some are very resistant to decomposition (for example plant lignin).

Decomposition of organic matter proceeds step by step so that a group of organisms, such as a group of bacteria, may use a particular organic substance, converting it into intermediary compounds which are subsequently acted upon by another type of bacteria, and so on. These intermediary compounds are called humus. Humus is a brown to black material. It is a stable fraction of the organic matter in the soil, being broken down only slowly.

Soil organic matter therefore comprises a series of compounds ranging from undecomposed plant (crop stubbles) and animal tissue, including urine and faeces of soil animals and animals grazing at pasture, to decomposing humus. Soil organic matter consists of compounds of carbon, oxygen, hydrogen, nitrogen, sulphur, potassium, and phosphorus. It also contains calcium, magnesium, sodium, and minor nutrient elements (copper, zinc, manganese, molybdenum, iron etc.). These elements are all eventually released in soluble forms to soil solution and so can be taken up by plants (mineralisation). Soil organic matter helps to bind inorganic soil particles (mainly clays and oxides) together, thereby improving soil structure. Organic matter has positive and negative charge sites on the surface, and so has an anion and cation exchange capacity, which can retain nutrient elements. The negative charge sites usually dominate, so the net surface charge of organic matter is usually negative, so the cation exchange capacity dominates. In addition, ions and molecules are adsorbed onto the surfaces of organic matter. This incudes iron and aluminium, which in turn can further adsorb other ions and molecules from soil solution. In addition organic matter forms a range of different compounds with many elements, such as copper and zinc, which can affect the supply of these elements to soil solution and so for plant uptake.

Retention of nutrient elements by soils

This section considers retention of nutrients by soil in greater detail.

Exchangeable cations and anions

The surfaces of inorganic and organic soil constituents have negative and positive charge sites which are balanced by cations and anions from soil solution. The cation and anion exchange capacities of soils provide a measure of the magnitude of the negative and positive charges of the soils surfaces as measured by the amount of cations and anions that balance the charge.

Some cations and anions exist in soil solution as simple ions. Examples of simple cations are sodium, potassium, magnesium, calcium and ammonium; examples of simple anions are chloride and nitrate. These ions are relatively chemically stable in solution in the simple form and so have little need to chemically react to achieve greater chemical stability. But they do neutralise charges present on the surfaces of soil constituents and so are retained by the soil as surface charge balancers.

Other ions (phosphate, molybdate, zinc, copper) are not chemically stable in solution, and achieve greater stability by reacting with ions and molecules in solution (precipitation) or on the surfaces of soil constituents (adsorption) to form more complex, insoluble, more stable compounds, achieving greater chemical stability for all the reacting species. Simple ions are frequently invoved in these reactions. For example phosphate ions in soil solution react with calcium ions in solution to form precipitates of calcium phosphates. Simple ions are often co-adsorbed with adsorbing ions or molecules. For example, zinc is frequently adsorbed onto positively charged iron oxide surfaces in association with the chloride ion, as the single positively charged $ZnCl^+$ ion, instead of the doubly charged Zn^{2+} ion that is more strongly repelled by positive surface sites. Consequently the $ZnCl^+$ ions are preferentially adsorbed by positively charged surface sites, and Zn^{2+} is preferentially adsorbed by negatively charged surface sites.

■ IMPORTANT CHEMICAL PROPERTIES OF WHEAT GROWING SOILS IN WESTERN AUSTRALIA *(continued)*

There are two types of charge on soil surfaces:

- A permanent negative charge on clay minerals – resulting from the replacement of cations of lower charge into positions in the clay crystals normally occupied by cations of higher charge. For example, the triple-charged aluminium ion often substitutes for the quadruple-charged silicon ion in the clay crystal. This leaves the crystal with a net negative charge. The double-charged magnesium ions often substitute for the aluminium ion in parts of the aluminium-silica minerals also creates a permanent negative surface charge.
- A variable surface charge is generated by the adsorption or desorption of hydrogen ions onto or from the soil surface. Hydrogen ions are positively charged so their adsorption increases the magnitude of the positive surface charge. Desorption of hydrogen ions has the opposite effect. The adsorption or desorption of hydrogen ions onto or from the surface, and therefore the sign and magnitude of the variable surface charge, depends on soil pH, the concentration of other ions in solution and the nature of the soil surface. This type of charge is common on the surfaces of iron and aluminium oxides, and on the edges of clay crystals.

Both types of surface charges are balanced by retaining anions or cations from soil solution.

In practice, there is a mixture of permanent and variable charge sites on the surfaces of soils, and even on the same surface. For example, the negative surface charge of kaolinite clay, the major clay in Western Australian soils, comprises both types of charge sites; the positive charge sites on kaolinite are variable surface charge sites. Some idea of the size of the cation exchange capacity (estimating the magnitude of the negative charge sites on the surfaces) on various surfaces is given in Table 5.1. Compared to other clay minerals, kaolinite has a very low cation exchange capacity (1 to 2 meq/100 g of soil, see Table 5.1), so even if kaolinite occurs as high as 10% in a soil, it provides very little cation exchange capacity.

Table 5.1. – Cation exchange capacity (permanent negative charge) of some soil constituents

Mineral	Charge (meq/100 g)†
Illite	10-40
Vermiculite	130-150
Kaolinite	3-15
Montmorillonite	90-110
Organic matter	200 (pH > 4)
Iron oxides	10

† Units: Milli-equivalents per 100 g, which is the same as cmole per kg.

Much of the cation exchange capacity of the light sandy soils in Western Australia therefore depends on the organic matter content of the soils. An organic carbon content of 1% is equivalent to about 2% organic matter and could provide 4 meq/100 g of soil. This would be equivalent to about 160 mg of potassium per 100 g of soil or 2,400 kg/ha per 10cm depth, if the exchange capacity only contained potassium.

For cations that just balance negative surface charge on soil surfaces, the strength of binding of the cations to these negatively charged surfaces sites depends on the nature of the surfaces, the magnitude of the charge on the ions, and size of the ions.

Cations with a single positive charge, such as sodium, potassium and ammonium, are less strongly retained to a negatively charged surface site than double-charged cations such as calcium and magnesium. Likewise, triple-charged aluminium ions are more strongly retained by the negative surface charge than double-charged calcium ions or single-charged sodium ions.

In solution, water molecules and cations and anions co-exist. Water molecules are dipolar, similar to a magnet, with one end of the water molecule being slightly negative (near the oxygen atom of the water molecule) and the other end is slightly positive (near the two hydrogen atoms that also make up the water molecule). So water molecules are attracted to both cations and anions; the positive end is attracted to anions and vice versa. Therefore, in solution, both cations and anions attract water molecules, but some do so more strongly, depending on the surface density of the charge and the magnitude of the charge. For example, the sodium and potassium ions both have one positive charge. But the potassium ion is bigger and so has a lower density of charge on its surface (charge per unit surface area) than the smaller sodium ion. So sodium ions attract water molecules more strongly. The water molecules that are attracted to (hydrate) the potassium ions are more easily displaced (less energy is required to remove the hydrated water molecules), so more potassium ions can get close to the surface and completely neutralise the negative surface charge. Thus, if the concentration of sodium and potassium ions in soil solution is the same, more potassium ions will balance the surface charge because the potassium ions are less hydrated.

Water molecules are more strongly attracted to magnesium ions than to sodium ions. Both these ions are about the same size, but the magnesium ion has two positive charges and the sodium ion has one. So the magnesium ion has a greater surface density of charge and so is more strongly hydrated (the water molecules around the magnesium ions are more strongly held to magnesium ions than the water molecules around sodium ions). However, the double-charged magnesium ions are also more strongly attracted to negative surface charge sites than the single-charged sodium ions. Consequently, despite being more hydrated, more magnesium ions balance the surface charge.

IMPORTANT CHEMICAL PROPERTIES OF WHEAT GROWING SOILS IN WESTERN AUSTRALIA *(continued)*

Calcium, magnesium, sodium, potassium and ammonium ions will be least mobile in soils with a high cation exchange capacity. This would include organically-rich soils or soils with high clay contents. The same cations would be leached from siliceous sands and gravels or soils with only kaolinite clay, particularly in soils with low organic matter.

The strength of retention of cations to soil determines which chemicals are present in a soil. For example, single superphosphate, containing 20% calcium, has been commonly used for subterranean clover-pastures growing on very sandy soils in high rainfall (greater than 600 mm annual) areas in Western Australia. These soils have low cation exchange capacities, and the calcium from superphosphate frequently displaces (exchanges with) naturally occurring soil potassium. Therefore, as more superphosphate has been applied to these soils, the displaced potassium is leached and the soils can become potassium deficient. As a result, the clover grows poorly, producing little seed, and fails to persist and disappears.

The success of using gypsum as a soil conditioner depends in part on the ability of calcium to exchange (replace) sodium on the charged surfaces of the soil.

Adsorption in soils

The chemistry of soil is the chemistry of the partitioning of substances between the gaseous, the solid and the solution phases. Partitioning between the solid and solution phase is the major process for most agriculturally important chemicals (fertilisers, herbicides, pesticides, fungicides, and soil amendments, such as lime to cure soil acidity and gypsum to improve soil structure).

There are two main processes that control the partitioning between solid and solution. They are precipitation and adsorption.

Precipitation is determined by solution conditions (the solubility of the precipitating element) and can occur without the presence of a solid phase.

Adsorption occurs at solid surfaces and can be thought of as surface-induced precipitation because adsorbing substances do not leave solution unless an adsorbing surface is present. Both processes are important methods of retaining nutrient elements resulting from chemical reactions of ions and molecules in soils, either in solution or on the surfaces of soil constituents. Neither reaction can be distinquished and so both processes are called sorption

A soil with a low sorption capacity for a nutrient will attain high solution concentrations at relatively low inputs of that nutrient. This means that fertiliser will be more efficient on a low adsorbing soil than on a high adsorbing soil where more nutrient is required to reach the same yield.

The system becomes more complicated for leaching soils because such losses will be greatest on the soil which has the lower sorbing capacity.

Thus, sorption is a two-edged sword, reducing leaching losses yet increasing the amount of fertiliser needed to grow profitable crops and pastures.

As more of a nutrient is added to a soil, then the capacity of the soil to adsorb the nutrient usually decreases. There are two possible reasons for this. Firstly, when a soil is newly cleared and developed for agriculture and fertilisers are applied for the first time, nutrient elements are initially adsorbed onto the most chemically reactive sorption sites that retain the nutrient more strongly so it is less readily leached or available to plants. These sites are saturated first. In time, as more of the nutrient is added to the soil, so a greater proportion is adsorbed onto less reactive sites which retain the nutrient less strongly so proportionally more is leached and available to plants. The second reason concerns changing the surface charge by adsorbing charged anions or cations. For example, phosphorus is usually adsorbed as phosphate anions which are negatively charged. Like all adsorbing species, it is adsorbed by surfaces with either positive, negative or no charge sites. But regardless, when the phosphate ion is adsorbed, it takes its negative charge onto the surface and so increases the negative charge of the surface. So as more phosphate is added to the soil, the adsorbed phosphate increases the negative charge of the soil, increasingly repelling negative phosphate ions in solution and so making it more difficult to adsorb further phosphate. Likewise adsorption of copper and zinc ions, which are positively charged, increases the positive charge on the soil surface, making it more difficult to adsorb further additions of copper and zinc, but increasing adsorption of negative phosphate ions. So increasing adsorption of phosphate ions due to increasing additions of fertiliser makes it more difficult to adsorb anions, such as molybdate, sulphate, fluoride and further additions of phosphate, but increases adsorption of cations such as copper, zinc, cadmium, cobalt and lead. Adsorption of cations (copper, zinc) has the opposite effect. This trend is more obvious when large amounts of nutrient are required regularly (e.g. phosphorus, which is usually applied annually), but is less obvious when smaller amounts of fertiliser are required less frequently (e.g. copper and zinc).

Chemicals (ions and molecules) can be adsorbed by soil surfaces that have no electrical charge or have a charge of the same sign as the chemical in question or have an opposite charge. Phosphorus, molybdenum, and sulphate will adsorb strongly to soils high in iron and aluminium oxides, and particularly on such soils with relatively high clay contents (wodgils, forest gravelly loams, karri loams). They will only be mobile on siliceous sands and organic (peaty) sands. Copper, zinc and cobalt are immobile and not readily leached on siliceous sands because these elements adsorb onto silicates that make up sand particles. Copper, zinc and cobalt adsorb strongly onto iron and aluminium oxides and clay minerals of all types. These elements precipitate from solution in neutral to high pH conditions, so they are immobile in heavy wheatbelt soils and calcareous sands.

■ IMPORTANT CHEMICAL PROPERTIES OF WHEAT GROWING SOILS IN WESTERN AUSTRALIA *(continued)*

Soils are a mixture of mineral and organic matter, some of which have large, chemically reactive surface areas. These surfaces are in contact with both air and water. The water contains many compounds and chemicals that can bind to the soil surfaces.

The soil particle surfaces can be classified into:

- Mineral: which can be crystalline and/or amorphous and either electrically charged or uncharged.
- Organic: which can be alive (biomass), freshly dead, or long dead (humus), which too can be charged or uncharged.

The chemicals of agricultural interest in soil solution can be simple or complex, organic or inorganic, and either uncharged, or carry a positive (cation) or negative (anion) charge.

The sources of the materials in soil solution are:

- weathering and breakdown of soil minerals; for example iron, aluminium, sodium;
- exudates and breakdown products of plant microbes and animals;
- gaseous inputs and salts in rainfall; and
- fertilisers and other human inputs; for example phosphatic fertiliser, trace elements, herbicides and pollutants.

Soil systems are very complex adsorbing systems because the materials in solution can react with some of the soil surfaces and with each other.

Soil pH

Soil pH is a measure of the concentration of hydrogen ions (H^+) in soil solution. It is expressed as the negative log of the hydrogen ion concentration in solution to create a simple scale of 1 to 14. A pH of 7 is neutral; pH values less than 7 are acidic; pH values greater than 7 are alkaline. Soil pH is a measure of the relative proportions of acidity and alkalinity in the soil solution. The pH is equal to 7 when there are equal amounts of acidity (hydrogen ions) and alkalinity (hydroxyl ions) in solution. If there are more hydrogen ions than hydroxyl ions, the pH is less than 7 and a soil is acidic. If there are more hydroxyl ions than hydrogen ions, the pH is greater than 7 and the soil is alkaline.

The pH of a soil is usually determined by measuring the pH of a soil/liquid suspension. The liquids commonly used include water or solutions of calcium chloride. Calcium chloride is now used in Western Australia.

However, the pH of a soil depends on the type and concentration of cations in the soil solution and so the conditions under which pH determinations are made must be specified if their value is to be interpreted correctly. For example, a soil pH of 5.0 measured in a soil/water suspension would prevent the nodulation of subterranean clover whereas no problem would be observed for a soil as acid as 5 if the pH had been recorded using a soil/calcium chloride suspension.

The soil to solution ratio used to measure pH can vary; a ratio of 1 part soil to 5 parts 0.1 M calcium chloride is used in Western Australia.

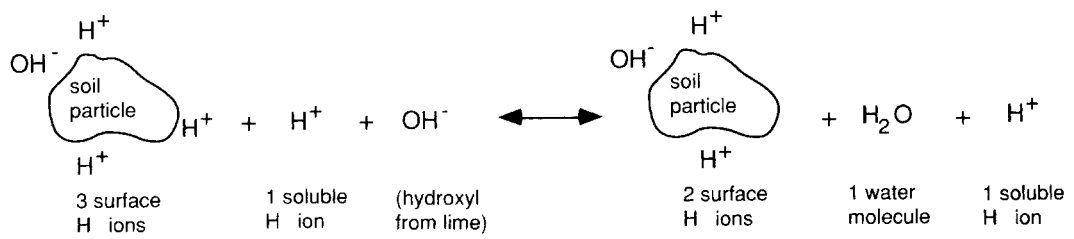
pH buffering capacity

Both hydrogen and hydroxide ions adsorb onto the surfaces of soil constituents. The amounts of hydrogen and hydroxide ions retained on soil surfaces are not determined by pH measurements, which measures the concentration of hydrogen ions in soil solution. The amounts of either hydrogen or hydroxide ions adsorbed are often referred to as the pH buffering capacity of the soil because they determine the ability of the soil to resist changes in pH. For example, if there are hydrogen ions on surface sites and lime is added to the soil, then hydrogen ions from surface sites will move into solution to resist the change in pH being brought about by the reaction of lime with soluble hydrogen ions (those in soil solution). This process is shown in Figure 5.1.

The pH buffering capacity of a soil is related to its cation exchange capacity. Soils with high exchange capacities have a greater ability to retain hydrogen ions and hence have a higher pH buffering capacity.

Many of the sandy (light) soils in Western Australia have low cation exchange capacities and pH buffering capacities. The total amount of hydrogen ions in a soil, which includes the amount of hydrogen ions in soil solution (measured by soil pH) or retained on the surfaces of soil constituents (estimated from the pH buffering capacity of the soil), determines soil acidity. The total amount of hydrogen ions in a soil is also measured by titrating a soil suspension with alkali and is called titratable

Figure 5.1



pH buffering.

■ IMPORTANT CHEMICAL PROPERTIES OF WHEAT GROWING SOILS IN WESTERN AUSTRALIA *(continued)*

acidity. Titratable acidity also determines the extent of rock phosphate dissolution in soils, and therefore how effective rock phosphates are likely to be for providing phosphorus for plants growing in that soil.

Soil pH can affect the supply of nutrient elements present in the soil for plant uptake. For example, as the pH of the soil is increased by adding lime, then copper, zinc and manganese are less soluble in solution so they precipitate out of solution, and/or adsorption of these elements by the soil is increased. Therefore, lower concentrations of these elements occur in soil solution and so less is available for plant uptake. By contrast, molybdenum becomes more available to plants as soil pH is raised. This is because molybdenum becomes more soluble and so more dissolves from insoluble sources in the soil and less molybdenum is adsorbed by the soil. Therefore, just like hydrogen and hydroxyl ions, most nutrients in the soil are also distributed between soluble forms in the soil solution and solid forms as shown in Figure 5.2. As the pH of a soil changes the relative proportion of the forms that a nutrient exists in will change which can alter the availability of a nutrient to plants (see Figure 5.3).

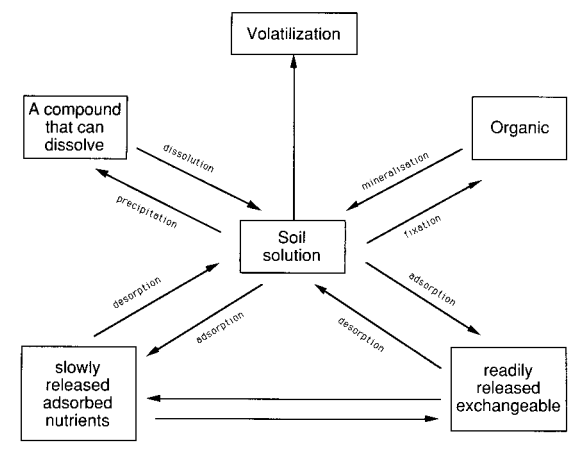
Fewer soil organisms exist in the soil as the soil pH (calcium chloride) decreases below about 5.0 or increases above 8.0.

Consequently, the pH of a soil has a significant effect on soil fertility because it can change the availability of plant nutrients, the physical fertility of the soil and the survival of microorganisms. Therefore it has the potential to be an accurate indicator of the suitability of a soil for plant growth.

Unfortunately, soil pH is sometimes difficult to measure and can vary between different sampling points in the same soil and between seasons. In addition, major differences in pH values occur if subsamples of the same soil are sent to different laboratories. This is because there are major differences in procedures used to measure soil pH at the different laboratories. Minor differences in procedures between laboratories also occur, which can affect pH values. For example, two different laboratories may measure the pH in 0.01 calcium chloride using a 1:5 soil to solution ratio and a standard temperature of 25 °C, but one laboratory may shake the suspension for 5 minutes while the other laboratory uses a 30 minute shaking time.

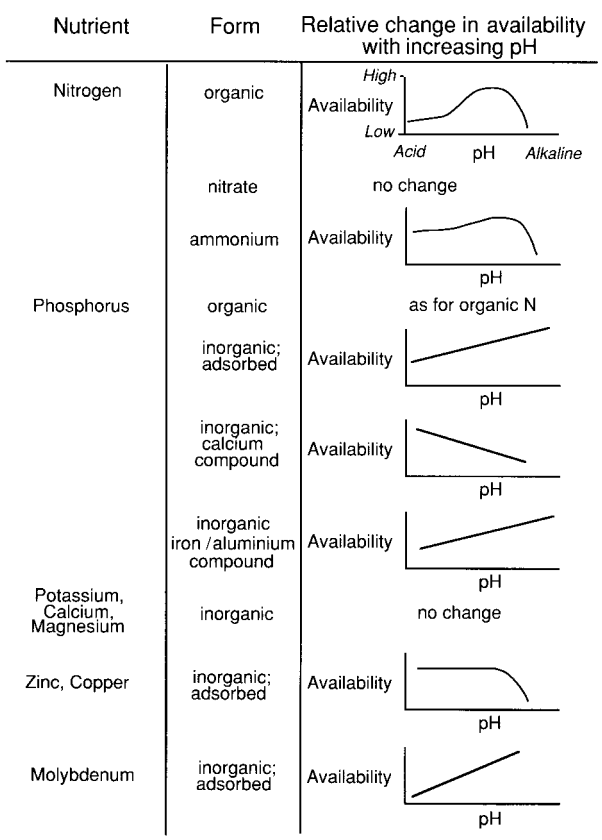
A pH (calcium chloride) between 5.5 and 6.5 is probably the most suitable for plant growth except for some legumes that are very sensitive to hydrogen ions.

Figure 5.2



The chemical activity in a soil.

Figure 5.3



Soil pH affects the availability of nutrients.

■ PHOSPHORUS

M.D.A. Bolland and J.W. Bowden

Western Australian wheat growing soils are mostly ancient and highly weathered with very low levels of natural (indigenous or native) phosphorus. When first cleared for agriculture, many of these soils were amongst the most acutely phosphorus deficient soils to be found anywhere in the World. On many of these soils, no wheat grain was produced unless fertiliser phosphorus was applied; in most cases the seedlings stopped growing when the phosphorus reserves in the seed were depleted, and due to lack of phosphorus in the soil, the seedlings eventually died.

Therefore, profitable wheat production on most wheatbelt soils of Western Australia has only been possible by applying phosphorus fertiliser to overcome the initial acute deficiency encountered in most of the newly and recently cleared soils. Before 1974, there was still a lot of land being cleared and developed for agriculture in Western Australia. Much of this land was suitable for producing wheat grain, and phosphorus was a major constraint to profitable grain production. At that time single superphosphate was the major phosphorus fertiliser used, and it cost $14 per tonne. To encourage farmers to use phosphatic fertiliser, the Commonwealth Government paid a bounty of $12 per tonne of single superphosphate, so farmers only paid $2 per tonne. This stresses how important overcoming phosphorus deficiency was at achieving profitable agricultural production in most newly cleared Australian soils; this was particularly so for wheat production in Western Australia.

Phosphorus is an essential component of cell membranes, plant genetic material and of the energy storage and transfer system for chemical reactions in plant cells. Early plant growth is particularly dependent on phosphorus because of the needs for rapid cell division and expansion. Phosphorus deficiency in wheat reduces tillering, head and grain numbers, and the primordia for all these are established as the seedling germinates and emerges from the seed, so very early in the development of the crop.

Symptoms of phosphorus deficiency in wheat are usually non-specific and difficult to diagnose in the field. In early development, the most noticeable feature of phosphorus deficiency in wheat is reduced growth and vigour. All the leaves become a dull dark green with slight mottling of the oldest leaf. On older leaves, chlorosis begins at the tip and moves down the leaf on a front while the base of the leaf and the rest of the plant remains dark green. Unlike nitrogen deficiency, necrosis of these chlorotic areas is fairly rapid, with the tip becoming orange to dark brown and shrivelling while the remainder turns yellow. At this stage the second leaf has taken on the early symptoms of phosphorus deficiency.

Fertiliser phosphorus is placed (drilled) with the seed of wheat while sowing crops at 3 to 5 cm deep, or it is spread over the soil surface of pastures grown between crops. Phosphorus taken up by plants and soil organisms (mostly present in the top 5 cm of soil) are returned as organic matter to or near the soil surface. Most of the soils used to grow wheat in Western Australia sorb phosphorus so little is leached. Consequently, most of the phophorus is present near the soil surface. Exceptions are for deep sandy soils in higher rainfall (greater than 400 mm annual average) areas with low capacities to retain phosphorus. In these soils, phosphorus is found at greater depth in the soil due to leaching down the soil profile. This has become more obvious after about 30 years after the land was first developed because it is possible to measure the phosphorus at depth as more is applied and leached down the soil. Examples are the deep sandy soils near Esperance, Badgingarra, Kojaneerup and Eradu.

Fertiliser phosphorus

Plant roots take up phosphorus from soil solution as water-soluble phosphate. The problem is that phosphorus is not chemically stable in a water-soluble form, and rapidly reacts, principally with iron, aluminium and calcium, present in soil solution and on the surfaces of soil constituents, to form insoluble, more stable compounds. These reactions continue, even when the soil is dry, albeit more slowly, to form even more stable and less soluble compounds. Consequently, fertilisers in which most of the phosphorus is present as water-soluble phosphorus are generally more effective than poorly soluble forms.

The original sources of phosphorus used in agriculture were animal manures, waste vegetable materials, bones, guano and rock phosphates, which contained no water-soluble phosphorus. Therefore, only soils with naturally large amounts of indigenous phosphorus could be used for productive, profitable agriculture. Single (ordinary) superphosphate was the first chemically prepared fertiliser to be manufactured on a large scale. The method of manufacture was first established in about the mid 1880s, and large scale production was achieved in the late 1800s and early 1900s, particularly after the first World War. As the World's population increased, the need for food required the development of soils that were phosphorus deficient for productive, profitable agriculture. Indeed, most soils developed for agriculture throughout the World were phosphorus deficient when first cleared of native vegetation. Therefore, the discovery of how to make single superphosphate had a huge impact on agriculture, making it possible to use these phosphorus deficient soils to feed the increasing world's population.

Single superphosphate (9.1% total phosphorus, 11% sulphur and 20% calcium) is made by adding sulphuric acid to calcium rock phosphates, known as apatite rock phosphates; typically 6 tonnes of acid is added to 10 tonnes of rock phosphate. The phosphorus and calcium come from the rock phosphate, and the sulphur from

PHOSPHORUS *(continued)*

sulphuric acid. Subsequently it was found that if a different ratio of sulphuric acid was added to apatite rock phosphate, phosphoric acid was made. The calcium sulphate (gypsum) also made is removed by filtration. Adding phosphoric acid to apatite rock phosphate makes triple superphosphate (20% total phosphorus, 16% calcium, and up to 1.5% sulphur from the small amount of gypsum or unused acid still present in the phosphoric acid). A local Western Australian version of triple superphosphate, called double superphosphate, contains 17.5% total phosphorus, 16% calcium and 3.5% total sulphur. Passing ammonia through phosphoric acid makes the ammonium phosphate fertilisers. The most common are monoammonium phosphate (MAP, containing 22% total phosphorus and 11% nitrogen) and diammonium phosphate (DAP, containing 20% total phosphorus and 18% nitrogen). Ammonium is a by-product of oil refining, so manufacturing plants that make ammonium phosphate fertilisers are located near oil refineries.

In Western Australia, local versions of ammonium phosphates, originally known locally as 'Agras' fertilisers, are made by adding ammonium sulphate to phosphoric acid, so the fertilisers contain sulphur in addition to phosphorus and nitrogen. An example is Agras No. 1, containing 7.6% phosphorus, 15.4% nitrogen and 11.5% sulphur.

The development of methods to make these manufactured, solid, granulated, stable fertilisers all had huge impacts on developing newly-cleared soils to grow profitable wheat crops Worldwide, particularly in Western Australia.

Single superphosphate is manufactured in relatively simple manufacturing plants. Such plants were developed on the sea coasts of various countries, including Western Australia. Good sea-port facilities were essential to import rock phosphate and elemental sulphur. Elemental sulphur is used to make the sulphuric acid that is then added to the rock phosphate to make the fertiliser. Rock phosphate used to manufacture single superphosphate in Western Australia was originally obtained from Christmas Island in the Indian Ocean, and Nauru and Ocean Islands in the Pacific Ocean. These days, the cheapest source of rock phosphate that contain low concentrations of cadmium for the manufacture of fertilisers in Western Australia are Morocco and other North African countries.

A major problem for the manufacture of single superphosphate was that the high quality apatite rock phosphates required contained at best 16% phosphorus. Therefore, 84% inert material needed to be transported vast distances to, in most cases, small manufacturing plants that supplied small local regions e.g. the Esperance region in Western Australia. The subsequent development of procedures to manufacture triple superphosphate and the ammonium phosphate fertilisers greatly altered the economic circumstances for manufacturing single superphosphate in the traditional simple, small plants in coastal localities around the World. Triple superphosphate and the ammonium phosphate fertilisers are made in much more complicated manufacturing plants. These are located at large deposits of good quality rock phosphate, so the need to transport rock phosphate over great distances is avoided; the rock phosphate is mined and used to manufacture the fertilisers at the same location. Only elemental sulphur, containing close to 100% sulphur, needs to be imported to make the sulphuric acid, which is used to make the phosphoric acid required to make the more concentrated phosphorus fertilisers. These large manufacturing plants are located close to oil refineries to obtain ammonia, and ammonia is used to make urea as well as the ammonium phosphate fertilisers. These plants make and export huge amounts of urea, triple superphosphate and ammonium phosphate fertilisers to all locations around the World and so provide strong competition for the traditional small single superphosphate manufacturing plants, including the four such plants that still operate in Western Australia (at Geraldton, Bunbury, Albany and Esperance). At the larger plants, giant freight ships are loaded with the fertiliser products, often before orders are received to supply the products. That is, often the ships have been loaded and left port before their final destination is known. As a result of these developments in fertiliser manufacture, wheat growers in Western Australia have access to both locally manufactured and imported fertilisers, which has helped to keep costs of fertilisers as low as possible.

The phosphorus compounds in the water-soluble manufactured fertilisers are monocalcium phosphate in single, double and triple superphosphates, in which about 80% of the total phosphorus in water-soluble, and ammonium phosphate in MAP, DAP or the Agras fertilisers, in which greater than 90% of the total phosphorus is water-soluble. These compounds are the few stable water-soluble phosphorus compounds that are suitable to make stable, granulated, solid fertilisers for use in agriculture. In field experiments, it is difficult to demonstrate differences in the effectiveness, for production of agricultural crops or pastures, of the two different water-soluble phosphorus compounds present in the different commercial manufactured fertilisers. Therefore, all these fertilisers are considered to be equally effective per unit of phosphorus.

All the manufactured, solid water-soluble phosphorus fertilisers are granulated (typically 1 to 5 mm) and are easy to handle, store and apply. Other essential nutrient elements can be incorporated into the granules if required, and so applied in the same operation. These include potassium, sulphur, copper, zinc, manganese, molybdenum and cobalt.

■ PHOSPHORUS *(continued)*

The fate of applied phosphorus

Phosphorus applied as fertiliser can be taken up (absorbed) by plants, retained by the soil, and lost through erosion or leaching.

The uptake of phosphorus by plants depends on the supply of available phosphorus in the root zone and the demand for the phosphorus by the growing crop. If growth rates are low for any reason then phosphorus uptake will be limited.

The supply of phosphorus to the plant is affected by:

- chemistry;
- the position of phosphorus in the soil – its placement, time of application and tillage practices;
- the presence of roots – determined by crop variety, growth stage, disease, hardpans, aluminium toxicity and soil wetting and drying, reduction in root growth caused by diseases, pests and herbicides; and
- the level of soil moisture – governed by rainfall, evapotranspiration and canopy development.

Many of these factors interact.

The supply of phosphorus depends on the concentration of phosphorus in the soil solution which is in contact with the roots.

Phosphorus in most soils is mainly derived from fairly recent applications of fertiliser. This means that the 'available' fraction of that phosphorus for plant uptake is unevenly distributed in the soil. Fertiliser phosphorus is drilled with wheat while sowing. Seed of wheat crops in Western Australia are typically sown 3 to 5 cm deep in rows that are about 18 cm apart. Therefore, the most recently-applied phosphorus is placed in concentrated strips in the soil at about 3 to 5 cm deep and 18 cm apart. Because the phosphorus will only move slowly to the roots and therefore not supply adequate phosphorus for profitable grain production, the roots must intercept the phosphorus in the soil as they grow through the soil.

The plant's yield response to fertiliser phosphorus is a response to the number of intersections the wheat roots make with concentrated zones of phosphorus in the soil and the concentration of phosphorus in those zones.

For freshly-applied phosphorus, the amount of soil affected will depend on the number of fertiliser granules and then on the ability of the phosphorus to diffuse from the granules into the soil. If soil moisture is high, more soil will be affected. If the capacity of the soil to retain phosphorus is high, less soil will be affected.

The amount of soil affected will increase in time as more fertiliser is applied and mixed through the soil as the soil is cultivated to sow crops.

Phosphorus fertiliser for wheat production

The water-soluble phosphorus present in the superphosphate and ammonium phosphate fertilisers is very hygroscopic. That is, the compounds strongly attract water, even attracting water vapour in relatively dry soil with moisture levels well below field capacity. The attraction of water, as vapour or liquid, to the granule develops what is called an osmotic gradient from the soil to the granule. As a result of this strong gradient, once the soil is moist, water is quickly drawn from the soil, either as vapour or as liquid, into the fertiliser granule. Once in the granule, the water rapidly and almost completely dissolves the water-soluble phosphorus compounds. The concentrated fertiliser solution then moves rapidly out of the granule and into the soil, driven in this direction by the large concentration gradient between the dissolved phosphorus compounds in the granule and the soil. The reactions between the water-soluble phosphorus in the fertiliser solution and calcium, iron, aluminium, and other elements, starts immediately, and commences in the fertiliser granule itself as soon as dissolution occurs. Rock phosphates used to make the water-soluble fertilisers frequently contain impurities of iron and aluminium, and are calcium phosphates, so the iron, aluminium and calcium react with the water-soluble phosphorus present in the granule. Once the concentrated fertiliser solution moves into the soil, which it does within seconds of dissolution, the water-soluble phosphorus in the solution reacts with many element in the soil solution and on surfaces of soil constituents, to form insoluble, more chemically stable, phosphorus compounds. Indeed, in the millimetres of soil near the fertiliser granule, the concentrated fertiliser solution has a low pH and it dissolves silica, iron, aluminium, calcium, manganese, magnesium and potassium present in very close proximity to the granule. All these dissolved elements partake in the reactions with the water-soluble phosphorus. As a result of the reactions, and in the soil just millimetres outside the fertiliser granule, the solubility product of many phosphorus compounds in the fertiliser solution is exceeded, so a range of different compounds precipitate out of the solution. In addition, water-soluble phosphorus is adsorbed onto surfaces of soil constituents by reacting with many elements, principally iron and aluminium, exposed at the surfaces of the constituents. The first precipitates and adsorbed phosphorus compounds formed are metastable, and a great deal of chemical reorganisation takes place; resulting in re-dissolution and desorption of phosphorus followed by further precipitation and adsorption reactions. The result of these continuing reactions is that more stable, less soluble phosphorus compounds are formed. These reactions continue to occur as the concentrated fertiliser solution moves out of the granule and further into the soil, so the solution becomes less and less concentrated as phosphorus and other elements (calcium, iron, aluminium) decrease due to precipitation and/or adsorption reactions. Precipitation reactions probably dominate within the granule and millimetres outside the granule. This is because of the relatively large phosphorus concentration in solution in

PHOSPHORUS *(continued)*

and close to the granule so that the solubility products of many phosphorus compounds in the solution is exceeded. Further out from the granule, the concentration of phosphorus in solution is much less and adsorption of phosphorus onto the surfaces of soil constituents is likely to dominate rather than precipitation of phosphorus from the soil solution. In practice, it is difficult to differentiate between precipitation and adsorption, so both are collectively called sorption reactions. The distribution of phosphorus in soil adjacent to a fertiliser granule varies markedly depending on the capacity of the soil to retain phosphorus. For a high phosphorus retaining lateritic Western Australian soil, about 55% of the phosphorus from a triple superphosphate granule was present within 5 millimetres of the granule after 4 weeks in the soil. The corresponding value was 28% for a low phosphorus retaining sandy podzol from Western Australia as a greater proportion of the phosphorus from the granule had moved out a greater distance into the soil.

The net result of the complex sorption reactions, is that: (1) the concentration of phosphorus originally present in the concentrated fertiliser solution decreases markedly with increasing distance from the granule into the soil, and the concentration of the sorbed phosphorus is greatest near the granule; (2) the agronomic effectiveness of the water-soluble phosphorus fertilisers is greatest immediately after dissolution of the water-soluble phosphorus initially present in the granule and the resultant fertiliser solution has entered the soil. This is because much of the phosphorus is present as dissolved phosphorus, as water-soluble phosphorus compounds, or as metastable precipitated phosphorus compounds which can readily re-dissolve, or as phosphorus adsorbed onto low energy sites that can readily desorb. However, in time, the continuing precipitation and re-dissolution, and/or desorption and adsorption reactions (sorption reactions) result in the formation of more stable less soluble compounds. Consequently, the agronomic effectiveness of the fertiliser-applied phosphorus for growing wheat plants decreases with increasing time from when the fertiliser granules were first moistened in the soil. As it turns out, wheat plants are well adapted to exploit this situation, as is now explained.

Wheat plants take up much water-soluble phosphorus soon after the seedlings germinate and emerge from the seed. It has been shown that the seedlings can rapidly take up most of the phosphorus that plant needs to grow and produce grain. Any large phosphorus deficiency during early growth greatly reduces grain yield potential at the end of the growing season. Field experiments have shown that applying fertiliser phosphorus to acutely phosphorus deficient soils 10 days after emergence of wheat crops produces an uneconomic increase in the grain yield. So in acutely deficient soils the phosphorus is needed early in growth. Once phosphorus is in the wheat plants, during subsequent growth, plants relocate the phosphorus from old tissue to newly growing tissue, including flowers and grain. For all the above reasons, it is recommended phosphorus fertilisers are drilled with the wheat seed at sowing. In this fashion, when the soil becomes moist and the wheat seedlings germinate and emerge, the water-soluble phosphorus from the fertiliser granules will dissolve and enter the soil near the roots of the germinating wheat seed.

Consequently, as much as possible of the water-soluble phosphorus dissolved from the fertiliser granule is taken up by the seedlings to ensure phosphorus deficiency does not limit grain production at the end of the growing season.

There is competition between the soil and plant roots for the water-soluble phosphorus dissolved from the granulated water-soluble fertilisers. Most of the phosphorus is sorbed by the soil. Only between 5 to at best 30% of the phosphorus is taken up by the plant. As the capacity of the soil to sorb phosphorus increases, so a greater proportion of the phosphorus is sorbed by the soil and plant roots take up a corresponding smaller proportion. But for any one soil, as more fertiliser phosphorus is applied, so the capacity of the soil to retain phosphorus decreases with increasing addition. Consequently, the agronomic effectiveness of subsequent applications of phosphorus for producing wheat grain increases and a greater proportion of the added phosphorus is taken up by the plant and a smaller proportion is retained by the soil.

The water-soluble phosphorus in the solid, granulated manufactured fertilisers does attract moisture from the air and this water will cause dissolution of the water soluble phosphorus present in the granules. This will only occur in the granules exposed at the surface of the stacks. Farmers store the fertilisers in dry storage sheds, or in stacks covered in tarpaulins. Some storage, both during transport to the farm and while applying the fertiliser, is necessary even if the fertiliser is purchased and spread as soon as possible. Longer-term storage needs to be in dry covered storage facilities.

To avoid congestion near the start of the growing season, fertiliser manufacturers and suppliers offer discounts to encourage farmers to purchase fertiliser months before the start of the growing season (i.e. in December instead of May). This fertiliser is often applied soon after purchase, often during summer when the soil is usually dry. However, early morning dews or summer rainfall, will result in the dissolution of the water-soluble phosphorus in the granule and its subsequent reactions with other elements and soil as described above. This will reduce the effectiveness of the phosphorus for growing wheat planted near the start of the next growing season. The decrease in effectiveness, relative to freshly-applied fertiliser phosphorus drilled with the wheat seed at sowing, is very obvious in acutely phosphorus deficient soils; it is not so obvious in soils that are only marginally deficient or possessing adequate levels of phosphorus for wheat

PHOSPHORUS *(continued)*

production. But farmers need to realise that fertiliser phosphorus applied in summer can lose up to half its effectiveness or even more by the time the next wheat crop is sown, so they may as well have only drilled half or less the amount of phosphorus with the seed while sowing the crop. Experiments done on soils that are no longer deficient in phosphorus will often indicate no grain yield differences for fertiliser applied either during summer or drilled with the seed while sowing near the start of the growing season. But the nil-phosphorus fertiliser treatment will also produce similar yields because enough phosphorus is being supplied by the phosphorus already present in the soil from fertiliser applied in previous years. No sensible conclusion about fertiliser effectiveness for producing wheat grain can be derived from such experiments. This does not mean that fertiliser phosphorus applied in summer will not lose effectiveness from early morning dews and summer rainfall, as is often implied by fertiliser suppliers and manufacturers; it has been clearly shown it will if a phosphorus deficient soil is used for the experiments to make meaningful comparisons between the different treatments.

The pH within the granules of the superphosphate and ammonium phosphate fertilisers is very acidic; pH values are typically 2.0 to 2.5. As stated above, as the dissolved fertiliser solution leaves the granule, its low pH can, within a few millimetres of the granule, cause dissolution of soil particles. It is stressed that research has shown the granules of the superphosphate and ammonium phosphate fertilisers have very little direct influence on the pH of soils. That is, the fertilisers do not directly change soil pH. Fertiliser phosphorus does this indirectly, by contributing to productive agriculture, as is discussed in the soil acidification section of this chapter.

Residual phosphorus

In the years after application of the superphosphate and ammonium phosphate fertilisers, the phosphorus from the fertiliser that is not lost by being removed in grain, eroded or leached, is present as: (1) undissolved phosphorus in old fertiliser granules, typically 10 to 20% of the total phosphorus applied; (2) sorbed by the soil; and (3) as phosphorus present in organic matter. The organic matter contains phosphorus taken up by plants and the many organisms growing in the soil and which has been returned to the soil as dead remains and bodies. In addition, soil animals and grazing animals (wheat and other crop stubbles, and pasture grown in rotation with the crops) return urine and faeces to the soil. All the sources (1) to (3) provide some water-soluble phosphorus for plant uptake in the years after application of the fertiliser and is called the residual value of the fertiliser. Research in the Western Australian wheat growing soils has shown that the superphosphate and ammonium phosphate fertilisers have a good residual value for grain production of wheat. As more fertiliser has been applied each year, the phosphorus status of the soils has increased. Eventually, most (70 to 100%) of the water-soluble phosphorus taken up by wheat plants has been provided by the residual phosphorus, with the remainder (30 to 0%) being provided by freshly-applied fertiliser drilled with the seed in the current year. In addition, the research has shown that as more fertiliser phosphorus is applied, the capacity of the soils to sorb phosphorus decreases. This is because as more phosphorus is added the freshly-applied phosphorus is sorbed onto chemically less reactive sites so it can more readily desorb. Also phosphorus is sorbed onto the surfaces of soil constituents as the negative phosphate ions. Therefore, as more phosphate is sorbed, the sorbed phosphate increases the net negative charge of the soil surface, making it more difficult to adsorb further negatively charged phosphate ions. So less phosphate is sorbed. The research has also shown that because phosphorus is less strongly sorbed by the soil as more fertiliser is applied, the effectiveness of subsequent applications of fertiliser phosphorus is increased for growing wheat plants. That is, as more phosphorus is added to the soil, then a smaller amount of freshly-applied fertiliser phosphorus is required to produce the same percentage of the maximum yield.

The supply of phosphorus from sources (1) to (3) in the soil is very dependent on seasonal growing conditions. Rainfall has been shown to have a big impact. In field experiments in Western Australia using wheat, it has been shown that the greater the growing seaon (May to October) rainfall, so the more effective are sources (1) to (3) at providing phosphorus to the crop for producing grain. That is, relative to fertiliser phosphorus drilled with the seed in the current year, a greater proportion of the phosphorus needed by the crop is provided from the phosphorus already present in the soil in wet years than in dry years. This is because in wet years more water-soluble phosphorus is released to the soil, and so is available for plant uptake, from sources (1) to (3) than in dry years.

The distance the dissolved phosphorus moves out of fertiliser granules when the granules take up water for the first time will vary depending on the capacity of the soil to sorb phosphorus. The distance is greater as the capacity of the soil to sorb phosphorus decreases. Therefore, the phosphorus will move further into the soil in sandy soils with low iron and aluminium, clay and organic matter contents, but it will move a much shorter distance in the high phosphorus sorbing soils, such as the Karri loams. In addition, for all soils, as more fertiliser phosphorus is applied, so further additions of phosphorus are less strongly sorbed, so the fresh phosphorus emerging from recently-applied fertiliser granules will move a greater distance into the soil.

Because it has a good residual value, phosphorus deficiency eventually becomes a minor problem, even in Western Australian soils that were originally so acutely deficient in phosphorus that no wheat grain could be produced if no fertiliser phosphorus was applied. So as the

■ PHOSPHORUS *(continued)*

phosphorus status of these soils has been increased by applying fertiliser each year for many years, only enough phosphorus fertiliser now needs to be applied to most of these soils to maintain the phosphorus status of the soils. This is to replace phosphorus removed in wheat grain (typically 0.25% phosphorus is present in the grain grown in Western Australia), lost by leaching and erosion, and which has become so strongly sorbed by the soil or incorporated in organic matter (humus) as to be essentially unavailable to crops.

Erosion and leaching

Some of the total supply of phosphorus in the soil can be lost if the fertiliser granules or soil/phosphorus reaction products are eroded by wind and water. On the siliceous sands or sesquioxide-free, peaty sand, the rainfall can leach phosphorus.

Seed phosphorus

When the embryo in the seed starts to germinate and grow, the seed itself provides most of the nutrients until a root system is developed that can take up significant amounts of nutrients from the soil. Dependence on seed phosphorus only lasts a few days. Most of the phosphorus needed by wheat plants to produce grain is derived from the soil.

Results from field experiments with cereals (wheat, oats and barley) have shown that in some years plants grown from seed containing high phosphorus concentrations have produced up to 20% more grain than plants grown from seed with low phosphorus concentrations. This may be due to the effect of stress experienced by the wheat plants during the growing season. Larger deeper rooted seedlings grown from seed of the same size but with higher phosphorus concentrations may cope better with water stress and/or stress caused by diseases, pests and herbicide sprays. Therefore, in some years these plants produce more grain than seedlings grown from seed of the same size but containing lower concentrations of phosphorus.

For wheat, yield increases due to seed phosphorus are unlikely when the phosphorus concentration in the seed is greater than 0.30%. Thus the seed for sowing the wheat crop should have over 0.30% phosphorus. Seed should be kept from the best paddocks – those that are fertilised and have the longest history of regular phosphate applications.

Seedlings grown from bigger seed produce bigger seedlings and sometimes produce more grain at the end of the growing season than seedlings grown from smaller seed. This is because larger seeds usually have larger embryoes and larger amounts of protein, carbohydrates and amounts of all plant nutrients than smaller seeds.

Rock phosphate

Long term (up to 20 years) field experiments with wheat in Western Australia have shown that all types of rock phosphates (reactive apatite rock phosphates – the most effective rock phosphates for direct application; low-reactive apatite rock phosphates – mainly used to make superphosphate and ammonium phosphate fertilisers; and calcium iron aluminium (crandallite millisite) rock phosphates – the cheapest source of rock phosphate for Western Australia) are highly unlikely to be profitable alternative phosphorus fertilisers to superphosphate and ammonium phosphate fertilisers. Relative to the effectiveness of freshly-applied superphosphate each year, the rock phosphates were from one third to one hundredth as effective, in both the year of application and subsequent years (residual value). Consequently, from about three to one hundred times the amount of phosphorus as rock phosphate, applied in the current or previous years, needed to be applied to produce the same yield as freshly-applied superphosphate.

Rock phosphates contain no water-soluble phosphorus. In fertiliser manufacturing plants, strong acid is added to rock phophate to make water-soluble phosphorus compounds. The hydrogen ions supplied by the strong acid dissolve the rock phosphate to make the water-soluble phosphorus compounds. When rock phosphate is directly applied to soils, the rock phosphate needs to react with moist soil to dissolve and produce water-soluble phosphorus, which can either be taken up by plant roots or sorbed by the soil. Hydrogen ions, supplied by the soil, are required to dissolve the rock phosphate to produce water-soluble phosphorus. The hydrogen ions can only be supplied in sufficient quantities for dissolution in acidic soils (pH less than 5.0 in calcium chloride, or pH less than 6.0 in water). However, most of the acidic soils used to grow wheat in Western Australia simply do not possess enough hydrogen ions to cause rapid and extensive dissolution of rock phosphate to supply enough water-soluble phosphorus for uptake by wheat plants to avoid phosphorus deficiency. This is particularly so during the early part of the growing season when wheat plants need adequate phosphorus to avoid phosphorus deficiency and achievement of maximum grain yield potential. The soils also must remain moist during this period otherwise rock phosphate dissolutions cannot occur. The fertilised soils used to grow wheat in much of Western Australia frequently dry out between rains throughout the whole growing season, including during early growth. Therefore, even if the soil did possess enough hydrogen ions to cause rapid and extensive dissolution of the rock phosphate early in the growing season, the lack of adequate moisture in the wheat-growing soils of Western Australia for most of the growing season is enough to prevent rock phosphate from being a profitable alternative to the manufactured granulated water-soluble fertilisers. The total supply of hydrogen ions in the soil affects rock phosphate dissolution including the hydrogen ions in solution (estimated by measuring soil pH) and on the surface of soil constituents (estimated

PHOSPHORUS *(continued)*

from the pH buffering capacity of the soil). The total supply of hydrogen ions in the soil available for dissolution of rock phosphate is measured by titrating the soil suspension with alkali (titratable acidity).

Rock phosphates are not suitable for alkaline soils because these soils contain too few hydrogen ions to cause any dissolution. Indeed, the most stable form of phosphorus in alkaline soils is apatite (rock phosphate). So once apatite is added to alkaline soils, it has no reason to react to achieve greater chemical stability, so it just remains as apatite in the soil.

Phosphorus and calcium are the major products of rock phosphate dissolution. Removal of the dissolved phosphorus and calcium due to sorption by the soil increases dissolution. However, once the capacity of soil to sorb phosphorus reaches moderate levels, the soil sorbs most of the phosphorus and wheat plants take up relatively little of the dissolved phosphorus. Consequently, in wheat growing soils in Western Australia, relative to superphosphate, the effectiveness of rock phosphate generally decreases as the capacity of the soil to sorb phosphorus increases.

Research in Western Australia has shown that, relative to superphosphate, the effectiveness of rock phosphates for growing wheat grain decreases with increasing amounts of application. This is because, like all insoluble compounds, rock phosphate particles will dissolve until the solubility product of the rock phosphate in soil solution is exceeded. The amount of phosphorus required to do this is the same, regardless of how much rock phosphate is applied. As more rock phosphate is applied, so the proportional dissolution from the rock phosphate particles decreases. Consequently, rock phosphates cannot support the same maximum yield plateau as superphosphate. So yield potential is forfeited if rock phosphate is used instead of superphosphate. By contrast, as explained above, as soon as the soil is moist after application, all the water-soluble phosphorus present in superphosphate rapidly and almost completely dissolves and moves out of the granule and into the soil.

In contrast to the solid, granulated superphosphate and ammonium phosphate fertilisers, to enhance fertiliser effectiveness, rock phosphates need to be applied as fine powders that are incorporated through the soil horizons explored by plant roots. In practice, for wheat crops this means at least the top 10 cm of soil where most of the wheat roots reside. Banding rock phosphates with the seed or at depth in the soil reduces its effectiveness; it needs to react with as much soil as possible to enhance its dissolution. Fine powders are difficult to handle, store and apply and mix through the soil using existing farm machinery.

As previously stated, rock phosphates were widely used in agriculture before the solid, granulated, water-soluble fertilisers were made. The manufacture fertilisers have enabled profitable wheat crops to be grown in phosphorus deficient soils all over the World. This is because they provide water-soluble phosphorus to meet the demand of the wheat plant during early growth. This is so regardless of the soil pH, the magnitude of the capacity of the soil to sorb phosphorus, and the rainfall zone. By contrast, rock phosphates can only be used in much more limited situations (acidic soils with adequate hydrogen ions with a low capacity to sorb phosphorus in a high rainfall (metres of annual rainfall) areas where soils remain moist for most of the growing season).

Calculating the most profitable amount of phosphorus to apply

To do this, it is first necessary to determine, for defined soil types and environments, the relationship between grain yield of wheat and the amount of fertiliser phosphorus applied in the year of application, known as the yield response curve (Figure 5.4). Examples of defined soil types and environments in Western Australia are the Eradu soils east of Geraldton, the loamy sandy soils in the Wongan and Ballidu region, the Kumarl clay soils near

Figure 5.4

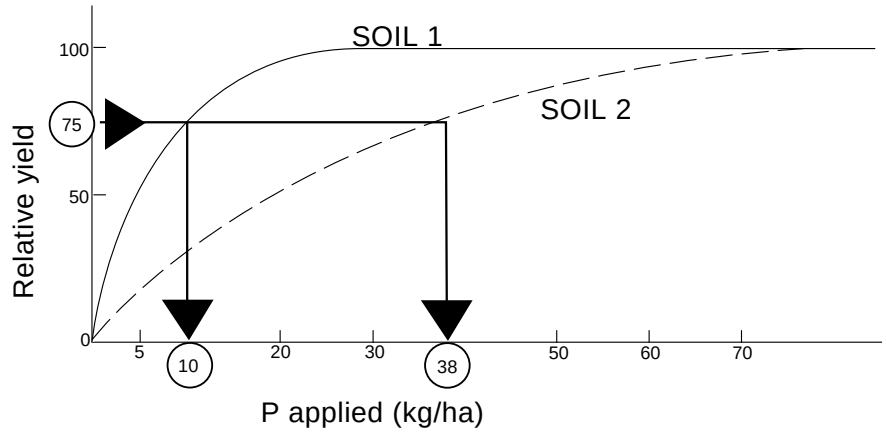


Figure 5.4 Relationship between wheat yield and applied phosphorus

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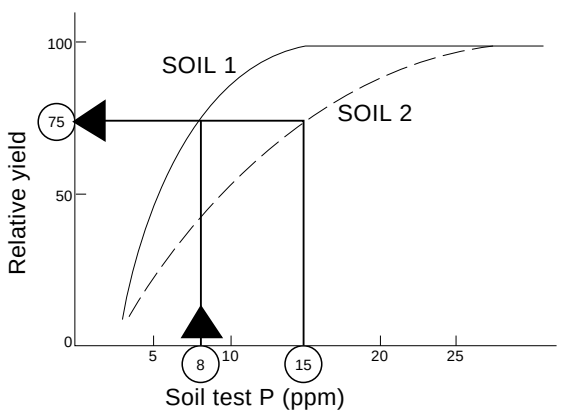
Salmon Gums, and the Fleming gravelly soils near Gibson. Yields are expressed as a percentage of the maximum (relative) yield, because for the same soil type and environment, yields vary from year to year due to different seasonal condition experienced in the different years.

Yield response curves are different for different soils and are largely affected by the capacity of the soil to sorb phosphorus. For example, in Figure 5.4, soil 1 has a much lower capacity to sorb phosphorus than soil 2. Therefore, to produce the same relative yield, more phosphorus needs to be applied to soil 2 than to soil 1. This is because a greater proportion of the phosphorus applied to soil 2 is sorbed by the soil so proportionally the wheat plants growing in soil 2 take up less of the applied phosphorus.

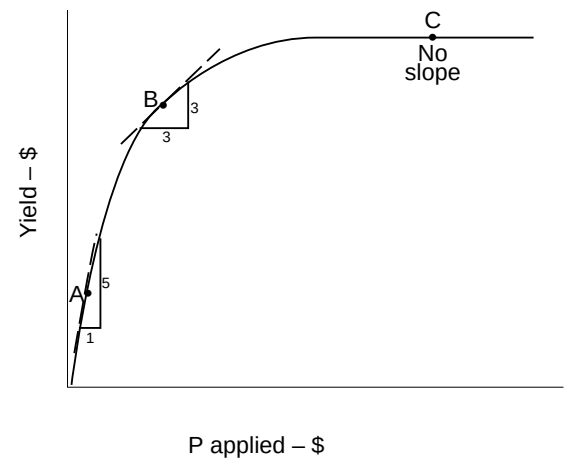
To define the complete yield response curve for each soil and environment, the experiments have been done on newly cleared soil that have not been fertilised with phosphorus in previous years. However, these days farmers are dealing with soils that have been fertilised with phosphorus in previous years. For each defined soil type and environment, the relative grain yield of wheat produced by the phosphorus already present in the soil, before any fresh fertiliser phosphorus is applied in the current year, needs to be determined. This is done with the aid of a soil test for phosphorus, using the soil phosphorus test calibration (Figure 5.5), determined for the same soil type and environment as the yield response curve shown in Figure 5.4. For the soil phosphorus test calibration, soil samples to measure soil test phosphorus are collected in January-February, and the soil test value is related to grain yields measured later on that year. In Western Australia, the soil test is measured using the Colwell procedure. The top 10 cm of the soil is used for the test. The soil phosphorus calibration is also largely affected by the capacity of the soil to sorb phosphorus, with larger soil test values being required to produce the same relative yield for soil 2 than soil 1, because soil 2 has a larger capacity to sorb phosphorus.

Figure 5.5



Soil phosphorus test calibration

Figure 5.6



Conversion of wheat yield and applied phosphorus to dollar terms

The soil phosphorus test calibration is used to predict wheat grain yields from the amount of phosphorus already present in the soil. How this is done for soils 1 or 2 is shown in Figure 5.5. The yield predicted from the soil phosphorus test calibration in Figure 5.5 is transferred to the yield response curve in Figure 5.4. It is then possible to determine the likelihood of obtaining a profitable return from money spent on applying fresh phosphorus fertiliser to the next wheat crop grown in that paddock. Figure 5.6 illustrates the simple theory of how the calculation can be made. Figure 5.6 is produced by converting grain yield of wheat and the amount of phosphorus applied to $ terms. This is done by multiplying yield, as tonnes per hectare, by the price paid per tonne of wheat. Costs include the cost of the phosphorus per hectare and the cost of application. At each point on the curve in Figure 5.6, marginal costs and returns can be estimated. Point A in Figure 5.6 is on the steeply rising part of the curve, so more dollars are returned for each dollar spent, and it is very profitable to apply fertiliser phosphorus to a paddock at about this part of the yields response curve. At point B in Figure 5.6, marginal costs equal marginal returns and the maximum profit is made by adding fertiliser phosphorus up to this point. At point C in Figure 5.6, there is no yield increase from adding fertiliser phosphorus, so money is better spent on some other factor limiting wheat yields.

■ NITROGEN

M.G. Mason and R.F. Brennan

Nitrogen is an essential part of many plant compounds such as amino acids and proteins.

Nitrogen also has an essential role in the production of chlorophyll, the compound which results in the green colour of plants and is essential for photosynthesis.

Plant deficiency symptoms

Within the plant, nitrogen can readily move to areas of active growth, which have high metabolic demand. Consequently, a symptom of nitrogen deficiency in plants is the yellowing of the lower (older) leaves of wheat due to nitrogen being remobilised and transported from the older tissues to the younger, actively growing, tissues.

Responses to additions of nitrogen fertiliser are generally in the form of greener plants due to increased chlorophyll production, and increased vegetative growth, photosynthetic areas and grain yield. The increase in wheat yield to added nitrogen is largely due to increased tillering but nitrogen fertiliser can also increase seed numbers per ear. In addition, a good supply of soil nitrogen can increase the concentration of grain protein.

On very nitrogen deficient soils, the wheat plants will utilise the added nitrogen to increase tillering and vegetative growth to set up grain yield potential through the production of more ears and seeds per ear. An increase in nitrogen supply also increases photosynthetic leaf area and this increases the potential for carbohydrates to fill the seeds. There maybe sufficient nitrogen for growth and little available for seed protein. However, if the supply of nitrogen in the soil is further increased, vegetative growth requirements are satisfied and more nitrogen in the plant is available to be transferred to the seed for protein production.

Seed protein comes from the late uptake of nitrogen by the wheat plant and the mobilisation of nitrogen from senescent (dying) lower leaves.

Soil organic nitrogen or nitrogen in legume residues can be more effective in raising the protein of seed than fertiliser nitrogen applied early in the wheat plant growth stage. The reason being that organic sources continually break down throughout the season resulting in a continual supply in plant available nitrogen. Fertiliser nitrogen applied late in the season has little effect on yield but will be available for transfer to the seed for protein production. However, fertiliser nitrogen has to be applied early to set up potential yield and unless excessive amounts are applied, little nitrogen is left for later uptake. For a wheat crop, if there is only a low supply of soil nitrogen early in the season yield potential will be low because tillering and hence ear numbers will be reduced.

The nitrogen required for successful growth of wheat must be supplied either by the soil or as fertiliser. The plants can only take up nitrogen from the soil when it is in an inorganic form, which is as ammonium or nitrate.

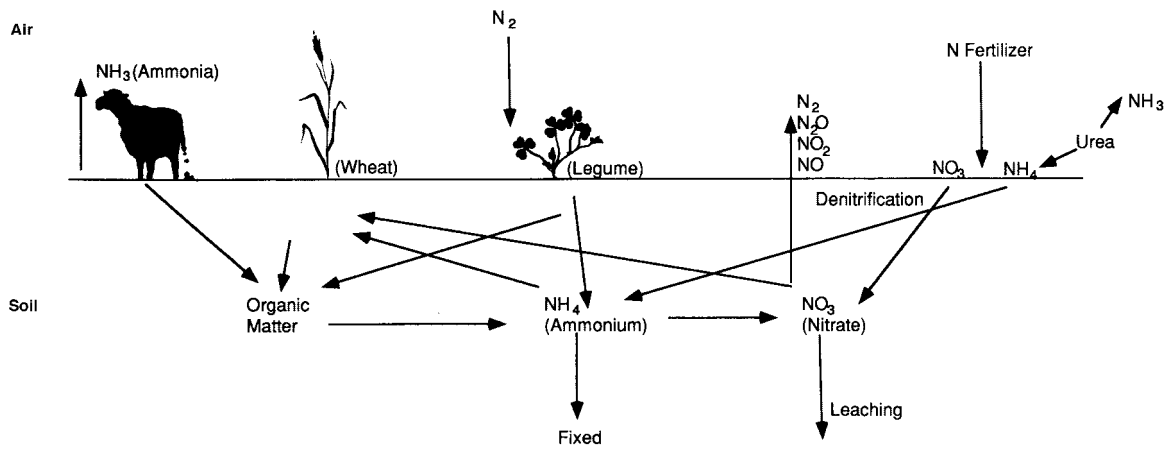
Nitrogen in the soil

In the soil over 98% of the nitrogen is in an organic form, which is not available to the plant until it is mineralised to inorganic forms. The organic matter varies in its nitrogen content and its ease of mineralisation, ranging from readily mineralisable recent crop or pasture residues to older, more stable organic matter, which is mineralised slowly.

Mineralisation continues throughout the growing season, providing a continuous supply of nitrogen, which may or may not satisfy the crop requirements, and which will vary with temperature and soil moisture. Mineralisation is stimulated by cultivation.

The nitrogen cycle is outlined in Figure 5.7.

Figure 5.7



The nitrogen cycle.

■ NITROGEN *(continued)*

A large part (sometimes all) of the plants requirement for nitrogen is supplied by the soil. However, where the available soil nitrogen supply is inadequate for optimum yields, nitrogen fertiliser needs to be applied to obtain maximum economic grain yields.

Distribution of nitrogen deficiency

In Western Australia, all soils are potentially nitrogen-deficient. The light or coarse textured (sandy) soils are very deficient. The heavy or fine textured (loam and clay) soils generally contain higher levels of nitrogen before they are cleared but intensive cropping with non-legume crops can deplete the amount of nitrogen in the soil.

Nitrogen deficiency is more likely in higher rainfall areas because of greater chances of leaching, especially on uniform coarse textured soils or because of losses through denitrification due to waterlogged fine textured soils or duplex soils with a slowly permeable subsoil.

The greatest responses to addition of nitrogen fertiliser will be obtained in higher rainfall areas on light (sandy)soils which have not grown legumes recently. The yield response to fertiliser nitrogen is affected mainly by:

- weather (mainly rainfall);
- soil type; and
- recent paddock history (whether a legume has been grown in the rotation).

These factors are included in the nitrogen recommendations, which are offered as a guide, to be varied with specific local knowledge.

Nitrogen requirement

A crop's requirement for nitrogen will depend on:

- season;
- soil type;
- paddock history;
- soil moisture; and
- yield potential.

Season

Larger yield increases will be obtained and more nitrogen fertiliser will be needed in high rainfall years, because higher yielding crops can be grown. A dry finish to the season will limit yield response.

If high rainfall causes waterlogging then the grain yield increase to nitrogen fertiliser will also be limited.

Soil type

Heavy soils naturally have more nitrogen and are less prone to leaching losses. Consequently these soils usually need less nitrogen added (often none) to produce optimum crop yields, unless they have been cropped intensively.

Paddock history

Legume pastures and to a lesser extent, legume crops such as lupins or peas add nitrogen to the soil. This reduces the need for fertiliser nitrogen compared with multiple cereal crops or where no legumes are grown in the rotation.

Soil moisture

Moisture stored in the soil at the beginning of the growing season can indicate the likelihood of a good growing season (particularly on heavier soils). Rates of nitrogen fertiliser could be varied accordingly.

Yield potential

For grain with a 2% nitrogen concentration, 20 kg of extra nitrogen will be contained in each tonne of wheat grown. If the nitrogen harvest index (the proportion of nitrogen in the plant which is contained in the grain) is 75%, then about 27 kg extra nitrogen is needed in the plant. Assuming a recovery of 50% by the plant, an extra 54 kg of nitrogen is needed in the soil for each tonne of grain produced.

If the potential yield is increased above the average potential, extra N will have to be supplied either by the soil or by extra nitrogen fertiliser.

Potential yield can be increased by:

- a good early start to the growing season which allows early sowing;
- using an appropriate high-yielding wheat variety on a productive soil type;
- effectively controlling weeds;
- being disease-free; and
- making sure other nutrients such as phosphorus, potassium, sulphur, copper, zinc, molybdenum and manganese are in adequate supply.

Sometimes a paddock has a higher potential because of a higher than normal soil nitrogen level after good legume pasture for a number of years. The requirement for fertiliser nitrogen could be lowered because of the greater supply of available soil nitrogen.

The amount of nitrogen to be applied to the wheat crop will be determined by economics. The optimum economic rate depends on the cost per unit of nitrogen in fertilisers and the price received for wheat grain. Economics are taken into account in making recommendations.

Deciding on the rate of application

Soil testing for nitrogen fractions has not proved successful. The nitrogen requirement of a crop cannot be indicated by the soil measurement (a nitrogen soil test) because the response to N depends greatly on the seasonal conditions which cannot be forecast.

The soil test cannot measure the nitrogen which will be available to the crop at important times during the growing season. A soil analysis however, will give a general idea of the total nitrogen status of the particular site.

Plant tissue can be analysed at various stages of growth and compared with standards, to diagnose nitrogen deficiency. However, as a predictive test to decide on application rates of nitrogen, tissue testing is still limited

NITROGEN *(continued)*

because by the time that there is sufficient growth to produce an adequate amount of tissue to test, the optimum time of fertiliser nitrogen application is likely to have already passed. Another problem is that a subsequent yield response to fertiliser nitrogen additions is still highly dependent on the conditions for the remainder of the growing season.

Sources of nitrogenous fertiliser

Sources of nitrogenous fertiliser for wheat growing in Western Australia are listed in Table 5.2.

Fertiliser nitrogen is added either as urea, ammonium-nitrogen or nitrate-nitrogen.

Urea is quickly broken down by moisture to ammonium-nitrogen. This process is generally complete within about one week, with most breaking down within three days. In most soils the ammonium-nitrogen is oxidised to nitrate by the process of nitrification. The rate of nitrification of ammonium-nitrogen depends on temperature, moisture and pH. The process is rapid (2 to 3 weeks) in alkaline or calcareous soils and slow in very acid conditions typical of wodgil soils. With ammonium sulphate or fertilisers based on ammonium sulphate (Agras), the rate of nitrification is generally slower than for urea or ammonium nitrate.

The form that the nitrogen is in the soil influences its availability to the plant and its losses from the rooting zone. If ammonium-nitrogen is applied on the surface, it stays in the surface layer while it is in the ammonium form. If the soil surface dries, this nitrogen is unavailable to the plant. Ammonium-nitrogen also is a positively charged ion and is held by excess negative charges on clay, sesquioxides and organic matter in the soil and so becomes immobile.

However, nitrate-nitrogen is a negatively charged ion and the soil has little or no hold on it. Consequently, nitrate is very mobile in the soil and can easily be lost by leaching in sandy soils, during heavy rains. In waterlogged conditions, the nitrate-nitrogen can be converted to various nitrogen gases by the process of denitrification and be lost into the atmosphere. Ammonium-nitrogen is not prone to denitrification.

An important factor in deciding which nitrogen fertiliser to use is the cost per unit of nitrogen, which can be determined by:

$$\text{Price/tonne nitrogen} = \frac{\text{Price per tonne of fertiliser} \times 100}{\text{\% N in the source}} \quad \text{(where N = nitrogen)}$$

Example

$$\text{Urea: Price/tonne N} = \frac{420}{46} \times \frac{100}{1} = \$913 \text{ or 92 cents/kg N;}$$

where cost of urea (ex works) = $400/tonne, freight = $20/tonne and the N percentage content of urea = 46%. The contents of nitrogenous fertilisers are listed in Table 5.2.

Table 5.2 – The main nitrogen fertiliser sources and their N concentration

Fertiliser	% N	% P
Urea	46	
Ammonium sulphate	21	
Ammonium nitrate	34	
MAP	10-11	
DAP	18	
Sodium nitrate	16	
Calcium nitrate	15.5	
Calcium ammonium nitrate	26	
Agras No. 1	17.5	7.6
Agras No. 2	12	10.4

NITROGEN *(continued)*

Sometimes a source other than the cheapest one can be used. For example, the convenience of using a compound fertiliser at seeding; the effect on disease (an ammonium source where take-all is present) or the effect of an acidifying source such as ammonium sulphate on availability of soil manganese. However, the economics of alternatives should be examined as well as the agronomic effectiveness of the nitrogen source compared to a delayed nitrogen application.

Time of application

Most grain yield increases to nitrogen fertiliser in Western Australia are due to an increased number of ears or grains per ear.

Grain yield increases are largely caused by increased tillering (seeds per unit area increases), which is determined early in the life of a wheat plant. The number of grains per ear are also determined early in the growth cycle/stage of the cereal plants). Therefore, there is a need for a good supply of N early in crop growth.

For sandy soils in higher rainfall areas, where the chances of leaching are higher, application of fertiliser nitrogen should be delayed 3 to 4 weeks. This allows the crop to establish a reasonable root system which helps the plant take up nitrogen from the soil and avoids large leaching losses. Optimum time of application of any one season can vary depending largely on the incidence of leaching rains in relation to time of application. Profitable responses can often be obtained up to 10 weeks after sowing in higher rainfall regions.

Generally, the later the application of nitrogen fertiliser, the lower the grain yield increase and the greater the chance of not getting economic grain yeild increase. Grain yield increases to later applications of N are generally due to better survival of tillers and to increased photosynthetic area and leaf duration.

Methods of application

There are two concerns with nitrogen application:

- The effect of placement of urea on losses to the atmosphere (volatilisation).
- The effect on germination of placing nitrogenous fertilisers with the seed – a toxicity problem.

Volatilisation losses of nitrogen

When urea is moistened and begins to break down, one of the intermediate products is ammonium carbonate, which creates alkaline conditions around the urea granule.

In the soil there is a balance between ammonium-nitrogen and ammonia.

Under acidic soil pH conditions, most of this nitrogen is in the ammonium form.

However, under alkaline soil conditions more ammonia is produced. If the fertiliser is on the soil surface, some of this ammonia will be lost to the atmosphere in the process called volatilisation.

The greatest loss by volatilisation is when the urea is topdressed onto moist alkaline soil and a period with warm temperatures and no rain follows.

Losses can be avoided by covering the urea with soil, for example, by topdressing immediately before sowing or where the nitrogen application is followed by rain heavy enough to wash the urea into the soil.

Ammonia losses are difficult to measure directly. Up to 20% may be lost in extreme conditions, but generally losses would be less than 10% in Western Australian conditions.

Volatilisation is generally not a problem with other nitrogen sources except on alkaline soils.

Toxicity

The ammonia produced when urea breaks down is toxic to germinating seedlings, so if urea is drilled close to the seed, it can reduce plant emergence.

The severity of the reduction depends on the amount of urea applied and the soil conditions at sowing and during germination of wheat seedlings. Reductions in germination of wheat seedlings will be worse with high rates of urea in moist soil but with no follow up rain for some time. If good rains follow sowing, the effect will be less.

If there is only a small reduction in plant numbers, say 10%, the crop can usually compensate by producing more tillers and grain yields may be unaffected, but higher losses of plants can reduce yields. If more than 30 kg/ha urea is drilled with the seed, yields can decline.

Except in alkaline soils, the other nitrogen sources do not produce toxic ammonia and are therefore less likely to reduce plant numbers or delay emergence. However, where the fertilisers are placed close to the seed in moist soil and there is a long dry period following sowing, plant numbers can be reduced because of the concentrated salt solution around the germinating seed.

Grain protein

Nitrogen is an essential part of protein, therefore, nitrogen supply is an important determinant of grain protein level. Many factors can affect grain protein, but the relationship between available nitrogen supply, yield response and weather conditions, particularly during grain-fill, is of major importance.

During grain-fill, the nitrogen taken up by the plant after anthesis is directed into the developing grain. Also, nitrogen in the plant vegetative parts is remobilised and transported to the developing grain. Therefore, nitrogen supply during the growth of the plant and a late supply of nitrogen to the plant could both be important in determining grain protein.

The grain protein concentration/percentage will depend on the amount of nitrogen available in the plant

NITROGEN *(continued)*

and the number of grains into which this nitrogen must be distributed. In addition, the protein concentration in the grain depends on how well the grain fills.

Hot, dry conditions during grain-fill affect carbohydrate deposition in the grain more than protein deposition. Therefore with a hot dry finish to the season grain protein concentration will be higher than when there is a cool, moist seasonal finish.

The relationship between grain yield response to nitrogen fertilisers and grain protein concentration is covered in greater detail in Chapter 7.

N sprays

N as a spray has a limited advantage of increasing grain protein of wheat seed when the spray is applied late (around the boot to anthesis growth stage). The results of increases in grain protein of wheat by foliar spray late in the season have been variable (from no increase to 10-15% increase in grain nitrogen concentration).

As the season progresses, the advantage of foliar spraying increases but it is generally ineffective depending on a range of seasonal conditions.

Effect on soil pH

All ammonium-N or ammonium-forming fertilisers potentially have a long term acidifying effect on the soil. During the nitrification or oxidation of ammonium-nitrogen to nitrate-nitrogen in the soil, hydrogen ions are produced in the soil and contribute to soil acidity.

Nitrogen sources (fertiliser, manure, legumes) containing or forming ammonium-N increase soil acidification. Also when nitrate-nitrogen is leached and cations move down the soil profiles are replaced by hydrogen ions, soils acidify.

The change in pH in the soil depends on the amount of fertiliser applied, the degree of leaching of the nitrate and the buffering capacity of the soil. Ammonium sulphate has a greater acidifying effect than urea or ammonium nitrate.

Table 5.3 – The effect of various N sources on the soil acidification of the soil, assuming leaching, and the amount of lime (calcium carbonate) required to neutralise each kilogram of N fertiliser

Nitrogen source	N%	kg $CaCO_3$/kg N
Ammonium sulphate	21	5.2
Ammonium nitrate	54	1.8
Urea	46	1.8
MAP	10-11	5.0
DAP	18	3.1
CAN	26	0.3-0.7

POTASSIUM

N.K. Edwards

Role

Potassium is a major plant nutrient, required by wheat in similar quantities to nitrogen. It is used in many plant processes including photosynthesis, transport of sugars, enzyme activation, maintenance of plant turgor and regulation of stomata. Plants deficient in potassium cannot use other nutrients and water efficiently and are less tolerant of stresses such as drought and waterlogging. Potassium deficient plants are also less resistant to pests and diseases.

The occurrence of potassium deficiency is determined by soil type, rainfall and management practices.

Soil type

Light textured (sandier) soils have lower potassium reserves than heavier textured (loam and clay) soils. The amounts and type of clay minerals present will have a large influence on the ability of a soil to retain and replenish potassium. So testing for potassium measures the potassium that is readily available to plants. This is either water soluble or exchangeable potassium that is retained on the surface of clay particles and organic matter. In most sandy soils, the potassium concentration is highest in the surface layer where potassium is associated with organic matter.

If clay or gravel occurs in the soil profile, then the potassium level may increase near the gravel and clay down the profile. However, it cannot be assumed that duplex soils will have high concentrations of potassium at depth. Recent sampling of a range of duplex soils indicates that there is wide variability in the potassium content of duplex subsoils. Even where exchangeable potassium levels do increase at depth, if root growth is restricted to the surface soil horizons by a change in soil texture, then plants may still not obtain sufficient potassium from the lower soil horizons.

Rainfall

Rainfall affects a wheat crop's requirement for potassium and the extent of leaching losses of potassium. Where the productivity of a crop is restricted by rainfall, the crop's demand for potassium will be low and deficiency unlikely.

Potassium leaches from sandy soils because they contain less clay and organic matter to retain the potassium in the root zone. Losses are minimal on clays and loams. Sandy soils in high rainfall areas will be the most vulnerable to leaching of potassium.

Management

A wheat crop's requirement for potassium will increase as yield increases. High yielding wheat crops put large demands on soil nutrient supply, particularly on light to medium soils. While a soil with low potassium levels may be able to supply sufficient potassium for a low yielding crop, when the yield potential is increased, potassium deficiency may develop. Management factors that increase the yield potential can affect crop demand for potassium. These include cropping intensity, crop yield levels, increased nitrogenous and phosphatic fertiliser rates, sowing date, weed control, timeliness of operations and removal of stubble residues.

Crop requirements for potassium change during the growing season. For wheat, potassium uptake is low at the beginning of the growing season when plants are small, but increases to a peak during late vegetative and flowering stages. The soil must be able to supply the crop's potassium needs during periods of peak demand.

There does not appear to be a single mechanism by which potassium deficiency limits yield. Potassium deficiency can affect leaf area, dry matter produced in upper internodes and ears, the number of grains per head or the seed weight. The root system of potassium deficient plants may also be poorly developed. Restricted potassium supply during early growth stages may be more harmful than later deficiency.

Symptoms

Potassium is very mobile in plant tissues. In deficient plants it is redistributed to new growth so that symptoms appear first in the older leaves. The symptoms of potassium deficiency in wheat are similar to those of nitrogen deficiency, but differ slightly in initially being more restricted to leaf tips and margins. Yellowing (chlorosis) and death (necrosis) of the tips of oldest leaves progresses down the margin to give an 'arrow' of normal tissue.

In wheat, the necrotic areas of the leaf have a distinct flame red appearance. There is premature death of the oldest leaves and the plants may be stunted, with shortened internodes. Stems may be weakened, causing lodging. These symptoms can be difficult to distinguish from those of some leaf diseases. Potassium deficiency can also resemble drought stress.

Soil levels

In cereals, soil testing for potassium is only of diagnostic value in identifying deficient areas. The test cannot be used to predict the amount of potassium required by the crop. Information on responses in wheat to additions of potassium fertiliser in Western Australia is limited. In Western Australia, the Colwell soil test is used to estimate the current potassium and phosphorus status of soils in the top 10 cm of soil. On sandplain soils with medium to high yield potential, economic responses to potassium are unlikely if the Colwell soil test is above 30 parts per million (ppm, or µg k/g soil, or mg K/kg soil).

■ POTASSIUM *(continued)*

On duplex soils, responses are more difficult to predict because of variability in the potassium supply from the subsoil and the ability of wheat plant roots to access this potassium. In paddocks with high yield potential, profitable responses in wheat have been measured where the soil test was up to 45 ppm. Where the soil test is above 30 ppm, topdressing test strips of potassium fertiliser onto the crop will help determine whether economic responses can be obtained.

Potassium fertiliser

Potassium chloride, known as muriate of potash, containing 50% potassium, is the cheapest potassium fertiliser available in Western Australia. It is imported, mostly from Canada. The fertiliser is composed of fine particles that are typically about 0.2 to 0.5 cm square and about 0.2 cm thick. The fertiliser is easy to cart, store and apply. Potassium chloride can be physically mixed with phosphatic fertilisers (single, double, and triple superphosphate, or DAP).

Potassium sulphate (25% potassium) is also available in Western Australia but it is rarely used for wheat crops. This is because potassium sulphate has about half the concentration of potassium as potassium chloride, so it is more expensive per unit of potassium, and more needs to be carted and applied. Also potassium sulphate is a fine powder that is more difficult to transport and apply.

Treatment

If a soil test shows that potassium levels are low, a decision about whether to apply potassium fertiliser will depend on soil type, rainfall and the expected yield of the crop. Where the paddock is in a cereal/legume rotation, applying potassium fertiliser in the legume year may increase the amount of nitrogen fixed for the following cereal crop, as well as improving the potassium status of the paddock. In low rainfall areas where the risk of leaching is low, potassium fertiliser can be topdressed following seeding. Potassium fertiliser should not be drilled with the seed as it can severely reduce germination.

In medium rainfall areas, it is better to delay fertiliser application until four weeks after germination, when the plants have developed a root system to take up the fertiliser. Where potassium deficiency is diagnosed in a crop, an economic response to applying muriate of potash will depend on how much growing season rainfall is left for the crop to respond to the fertiliser. Applying muriate of potash at 40 to 80 kg/ha ha generally given the most economic responses to potassium in wheat.

SULPHUR

R.F. Brennan and M.D.A. Bolland

Sulphur deficiency has rarely been diagnosed in wheat crops in Western Australia because of the widespread use of single superphosphate containing 10.5% sulphur. Deficiencies of sulphur are most likely to occur on the deeper sandy soils of the wetter margins of the wheatbelt, in situations where triple superphosphate (containing up to 1.5% sulphur) or DAP (containing up to 1% sulphur) have been used for several years.

Symptoms

With low nitrogen, sulphur deficient plants have pale younger leaves, growth is retarded and maturity delayed. Where nitrogen had been applied, the sulphur symptoms become more severe. The entire plant becomes lemon yellow and stems redden. Symptoms for sulphur deficiency differ from those of nitrogen deficiency where old leaves are severely affected first.

Deficiency most often occurs in the wetter years and progressively becomes more severe with successive years when using fertiliser with low sulphur concentrations (DAP, triple superphosphate).

Treatment

Sulphur deficiency can be avoided by using sulphur containing phosphorus fertilisers supplying 5 to 10 kg sulphur/ha. These sulphur containing fertilisers need to be used in rotation with DAP or triple superphosphate in a fertiliser strategy.

Diagnosis

Tissue test can act as a rough guide; 0.2% sulphur in younger leaf tissue is the critical level used for many crops, but often the nitrogen to sulphur ration (N/S) is also a valuable guide. A ratio of greater than 19:1 often indicates sulphur deficiency.

A sulphur soil test has been developed for sulphur and is being tested in Western Australia. A soil test value of less than 10 ppm is suggested as indicating likely sulphur deficiency, but this has yet to be confirmed for wheat grown in field experiments on a range of different soils in Western Australia.

■ COPPER

R.F. Brennan

Copper deficient soils are widespread in Western Australia. An estimated 8 million hectares, consisting of one-third of south-west Western Australia, has received copper in fertilisers.

Distribution of copper deficient soils

In Western Australia, copper deficient soils are widespread and have been identified on: calcareous aeolian sands formed on coastal dunes, organic soils, a range of soils formed on sandstones in Gingin-Dandaragan districts, calcareous loamy sands and siliceous sands formed on marine limestone, soils with coarse textured A horizon (< 15% clay, 0-10 cm) formed from acid igneous and sedimentary materials such as laterite, dissected laterite, granule granitic, gneisses and occasionally fine textured soils formed from acid igneous or sedimentary materials.

Copper in wheat plants

Copper is an essential component of many plant enzymes such as ascorbic acid oxidase, stocyanenocyanin, superoxidase dismutase and amino oxidase.

Copper is also essential for lignification which gives the wheat plant structural strength. 'Wilting' of Cu deficient plants is caused by structural weaknesses.

Copper deficiency also interferes with reproductive processes. The deficiency appears to interfere with pollen development at or near the stage of meiosis of pollen mother cells resulting in sterile pollen, which leads to poor grain formation and shrivelled grain.

Factors influencing uptake by wheat plants

Copper and nitrogen

Increasing the soil nitrogen either from the addition of nitrogen fertilisers or by legume pastures can induce copper deficiency in wheat. The increased supply of soil nitrogen increases the yield potential so that there is also a greater copper requirement, which can induce copper deficiency in wheat plants grown in soils with a marginal copper supply. It is observed that nitrogen fertiliser severely depresses the copper concentration in the wheat shoots by promoting rapid growth of wheat plants compared to root growth. The movement of copper within the plant, especially from old leaves to new leaves depends on the nitrogen status of the plants. Under high nitrogen status, there is little of no movement of copper from old leaves to the new growth of wheat plants.

Copper and liming

The adsorption of copper by soil surfaces increases with increasing soil pH. Adding lime to soils increases soil pH, thereby increasing adsorption of copper by the soil, and so reducing the amount of copper in soil solution. Therefore, liming would be expected to lower the copper availability to plants. This has not always been observed and soil pH is often found to have a smaller effect on the availability of copper as measured by plant uptake.

Copper and herbicides

Glasshouse work has shown that chlorsulfuron and diclorfop-methyl can decrease the uptake of copper (and zinc) were incorporated together in the soil. In the field, chlorsulfuron decreases the concentration of copper in shoots by as much as 30% which can induce copper deficiency in wheat plants if copper soil supply is marginal.

Copper and Zinc

Copper deficiency can be induced in wheat plants if zinc fertilisers are applied. This interaction is only of significance if copper supply in the soil is marginal and appears to involve competition in uptake between copper and zinc by plant roots. Therefore, if copper is adequately supplied to the soil the addition of zinc fertiliser is unlikely to induce copper deficiency.

Symptoms of deficiency

The symptoms of copper deficiency reflect its function in the plant.

With increasing severity of copper deficiency the symptoms are:

- Weak stems between the ear and top node because lignification is restricted.
- Leaves of copper deficient plants readily become limp as they lose water during warm, dry periods of the day. This may be confused with moisture stress or wilting. In severely deficient plants, leaves may completely collapse about midway between tip and base. This is easy to confuse with manganese deficiency.
- Restricted grain filling – mildly copper deficient plants produce shrivelled grain but this may be confused with effects of root rots, frost, drought, herbicide damage or molybdenum deficiency.
- Partially filled ears – pollen sterility produces uneven or complete failure of grain-set in the ears. Affected glumes have a loose, open appearance, which can be confused with effects of root rots, frost, drought, herbicide damage or molybdenum deficiency.
- Empty ears – pollen sterility or premature death of developing reproductive tissue produces empty ears.
- In copper deficiency, dead tissue is typically white at first but may darken. Tip glumes may be more affected than basal glumes giving a 'rat-tail' appearance to the ear which can be confused with roots rots, frost, drought, herbicide damage, or molybdenum deficiency.
- Blackening – conditions such as copper deficiency that may inhibit grain filling, grain setting or ear and glume formation without killing the vegetative portion of the plant, often lead to the accumulation of sugars in the stems and ear tissues. This often produces dark pigments as the tissues dry off. Blackening due to copper deficiency may be confused with effects of septoria, frost, drought, herbicide damage or

COPPER *(continued)*

mechanical damage such as from galahs nipping off green ears.

- Death of growing points – copper deficiency may stop production of new leaves and the ear. The first tiller is usually less affected than secondary tillers. Successive tillers are produced and abort until all growing points die. This can be confused with root rots, herbicide and insect damage.
- Bleaching of leaf tips – moderate and severe copper deficiency stops chlorophyll production in youngest developing leaf tissue. This usually shows as yellow-white tissue extending back from the tip of the youngest expanded leaf, while any emerging leaves are usually totally affected and eventually die.

Degrees of copper deficiency

Slight deficiency

In slight copper deficiency most ears are filled with plump grain but there are a few shrivelled grains or empty ears.

The straw is weak below the ear, stems bend and snap easily and are prone to wind and hail loss. Straw occasionally turns purplish-grey on the sunny side and darkening or blackening may be seen around nodes and on glumes.

There are no leaf symptoms.

Slight deficiency is unrecognisable before maturity and is usually only noticed during harvest.

Grain yield loss may be up to 20%, or higher where ears fall to the ground.

Mild deficiency

Most ears contain only shrivelled grain, some ears are empty and an occasional tiller is aborted when deficiency is mild.

Often straw is purplish-grey on the sunny side, nodes are blackened and glumes are darkened.

Affected plants remain green after unaffected plants mature. Occasionally some slight symptoms are seen on leaves but generally the deficiency is unnoticed until healthy crops are maturing or during harvest.

Grain yield loss is 20 to 60%.

Moderate deficiency

In a moderate copper deficiency, there are few normal ears. The grain is shrivelled and many white, empty, rat-tail or tipped ears are formed. Aborted tillers are common.

Straw is often darkened and plants tend to stay green and continue tillering.

The youngest expanded leaf is white of yellow-white back from tip or has broad yellow streaks. Often this seen only on the flag leaf while older leaves appear normal. The emerging leaf is yellow-white. It dies and the tiller aborts. The leaf tips turn pale brown, roll and twist after death.

The plant appears slightly pale and limp but this is not noticeable unless it can be compared to healthy plants. Older leaves are darker green and appear normal.

Root development is poor.

A moderate degree of copper deficiency can be readily identified when it occurs, but in the less severe cases may only become obvious at the flag leaf stage.

Grain yield loss is 50 to 90%.

Severe deficiency

Nearly all tillers abort, nearly all ears die prematurely and most fail to fully emerge from the boot when copper deficiency is severe. Plants continue to tiller to produce a 'grass clump'.

Plants are generally pale and limp, even older leaves may be affected so that the contrast between oldest and youngest leaf may not be marked and resembles manganese deficiency.

The tips of the youngest leaves are white to yellow-white. They die, become pale brown and often roll or twist. Roots are very poorly developed.

Severe deficiency can be seen from early growth stages through to when ears would normally emerge. It can be seen as early as two weeks after germination when seed low in copper is sown on severely copper deficient soil.

Grain yield loss is 90 to 100%.

Treatment

A single application of 3 to 9 kg/ha copper sulphate provides enough copper for maximum yields for most copper deficient soils of Western Australia.

Forms of copper

Many compounds are effective in supplying copper to wheat plants when applied as fine powders. However, copper oxide mixed dry with superphosphate was only half as effective as copper sulphate. Both sources appear to be equally effective when granulated with superphosphate. Slow release sources do not have any real advantage over copper sulphate in the field because copper sulphate reacts with the soil to become a slow release fertiliser. Copper chelates that have high mobility and solubility in soil solution may appear to have an advantage for increased availability for plant uptake. However, this advantage is lost or partly lost when iron and calcium ions replace the chelate copper.

Copper ore as long as it is the carbonate ore has been successfully used as a copper fertiliser for wheat. The sulphide ore has been ineffective in overcoming copper deficiency of wheat.

All sources have different concentrations so copper within the product and amounts applied to the soil need to be corrected for the recommended rate (based on copper sulphate). For example, if the recommended level of copper for a soil is 1.5 kg copper/ha, then 6.0 kg copper sulphate (25% copper), 3.0 kg copper oxychloride (52% copper) or 15 kg/ha copper carbonate ore (10% copper) would need to be applied.

COPPER *(continued)*

Placement

Distribution of copper through the soil is critical to its availability to wheat plants. As copper is immobile in the soil, wheat plant roots can only take up copper if they are in the vicinity of particles containing copper. The effectiveness of copper fertiliser is therefore dependent on the number and position of the copper particles per unit volume of soil. Banding of copper with the seed is more effective than topdressing and cultivating the soil that has been banded with copper also increases the effectiveness of the fertiliser. Topdressing copper fertiliser is usually a very ineffective way of trying to correct copper deficiency unless the topdressed Cu is subsequently mixed (cultivated) throughout the soil. Copper fertiliser is ineffective in soil containing few roots; e.g. surface soils whether plants are growing on subsurface (> 10 cm) moisture. Wheat plants can be severely deficient in these situations even though fertilisers containing copper have been evenly applied throughout the surface soils.

Large granules of fertiliser containing copper are much less effective than smaller or fine granules mainly because doubling the granule size reduces the number of granules per unit volume of soil by up to one eighth (based on spherical granules.).

Re-application has not been necessary in experiments as long as 30 years after the initial application – except where the initial application has not been high enough to satisfy the need of crops grown under extremely high nitrogen supply.

Residual value

Copper application generally has a long lasting effect in the soil (called residual value). A single application of 3 to 9 kg of copper sulphate per hectare provides enough copper for more than 100 years of cropping with present agricultural systems within Western Australia.

Copper trials based on various copper deficient soils to measure the residual value have suggested that copper fertiliser when applied at recommended levels lasts at least 20 years to 35 years. The residual value of previously applied copper compared to freshly applied copper was measured on farmer properties throughout the Lakes, Jerramungup and Esperance districts and the copper was found to be fully effective 23 years after the initial application.

Soil and tissue levels

Soil analysis for copper can easily give erroneous figures and interpretations, but when used correctly, copper extracted from soil by ammonium oxalate can show how much copper the soil is capable of supplying to plants. It can also indicate whether copper fertilisers have previously been applied to a paddock, which is useful, if a property changes hands.

When a soil is extracted with ammonium oxalate a copper level of 0.3 (mg/kg) parts per million (ppm) or less in the top 10 cm of a soil indicates almost certain deficiency for wheat, 0.3 to 0.8 ppm copper may be deficient and 0.8 ppm copper and above is almost certainly adequate. The DTPA soil extraction procedure has not been calibrated for Western Australian soils on which wheat is grown to diagnose deficiency of copper.

Wheat tissue analysis

Analysis of the youngest emerged blade (YEB) at the 5 to 8 leaf stages, but before flowering, provides the most accurate method of assessing copper status of the wheat plant. Provided the sample is not a mixture of copper deficient and healthy plants, the interpretation is relatively simple.

Interpretation of results from analysis of the copper status of the YEB can be summarised as:

Copper (ppm)	Status
2	Healthy
1.6 to 2	Marginal
1.3 to 1.6	Mildly deficient
Less than 1.3	Moderately to severely deficient

Grain

Analysis of grain for copper has limited usefulness, especially, if the sample is collected from both deficient and adequate plants (i.e. a harvester sample). If copper deficiency is suspected at harvest it would be better to obtain both adequate (plants not displaying symptoms) and deficient plants where heads are 'rat-tailed' and grain shrivelled. However, trials from Western Australia have given some indication of copper levels required on the grain for yield responses to applied copper for wheat.

Table 5.4 – Copper concentration in wheat grain

Cu concentration (mg/kg)	Likelihood of copper deficiency
0.9	Severely copper deficient
1.0-1.2	Sometimes copper deficient on marginal soil supply
1.3-1.5	Rarely copper deficient
1.6-1.8	Low, but not deficient
1.8-2.9	Normal
> 3.0	Sufficient

Copper may also be involved in the bread-making qualities of wheat grain. This aspect of copper nutrition has not been investigated within Western Australian agriculture.

■ ZINC

R.F. Brennan

Zinc deficiency in agricultural plants, including the cereals wheat, barley, and oats, has been widely reported in Western Australia. The need for zinc for plants was first established in the 1930s, when its importance for the growth of wheat (and pasture species) was shown. Since that time, zinc has become an important fertiliser for cereals grown in soils of south-western Australia.

Zinc functions

Zinc is involved in the enzyme systems of wheat plants and is essential for promoting metabolic reactions. Zinc is essential for the production of chlorophyll and carbohydrates within a plant. As a component of proteins, zinc acts as a functional, structural and/or regulatory factor in a large number of enzymes. Many of the physiological effects resulting from zinc deficiency are associated with the disruption of normal enzyme activity.

Photosynthesis, root membrane leakiness, auxin metabolism and reproduction are all affected by zinc deficiency. Zinc also is involved in the RNA and DNA structures of plants. Wheat grown on soils of Western Australia is particularly susceptible to zinc deficiency .

Distribution of zinc deficiency

Extensive areas of zinc deficiency in wheat occur in Australia. In western and southern Australia wide-spread zinc deficiency occurs in several million hectares of calcareous, and siliceous sands and loams as well as acidic soils. The most extensive area of zinc deficient soils comprises of 8 million ha in south-western Australia.

Zinc deficiency in wheat plants appears where zinc has not been applied to inherently deficient soils or where plant-available zinc in the soil has declined to inadequate levels.

Zinc deficiency in wheat has been reported to be associated with soils with both high soil pH (alkaline) and low soil pH (acidic) that have low extractable zinc. Zinc deficiency has also been observed in wheat grown on limed soils. That is, the rise in soil pH (less acidic) has induced Zn deficiency in wheat.

On light soils, after the initial zinc deficiency is corrected, the zinc supply is maintained at adequate levels for unimpaired plant growth by applying ordinary superphosphate containing 400 parts per million (ppm) zinc at 150 kg/ha or more.

The zinc impurities (60 g/ha) contained in this amount of superphosphate will often correct the zinc deficiency in some soils. In these circumstances no further zinc fertilisers have been needed. However, applying less than 150 kg/ha plain superphosphate or using low-zinc fertilisers such as imported DAP, causes the zinc supply to decline and wheat yields may be reduced.

Symptoms of zinc deficiency

The symptoms of zinc deficiency in wheat are usually seen on young seedlings early in the growing season. Zinc deficiency is more severe when light intensity is moderate and soils are cool and wet.

Deficiencies in wheat usually show on the middle leaves and extend into the new growth. The degree and extent of the symptoms depend on the severity of the deficiency.

One symptom suggestive of mild zinc deficiency is a longitudinal pale green stripe on each side of the mid-vein of fully emerged leaves. The leaf tissue in this strip soon dies and the necrotic (dead) area turns a pale brown. In some plants, this stripe may occur only on one side of the mid-vein. Necrotic patches usually appear along these stripes. The leaf changes from green to a muddy greyish-green in the central areas of the middle leaves.

As the deficiency becomes more severe, there is a general paling (chlorosis) of the leaves. Stunted plants often have 'succulent-looking' leaves or 'diesel-soaked' leaves, showing necrotic areas about halfway along the leaves, causing them to bend in the middle section. The necrotic areas increase and are surrounded by yellow-mottling areas. At this stage the plants' middle leaves collapse in the centre, causing leaf tips to droop. These symptoms are generally more advanced in the older leaves.

While grain yields may be greatly reduced in the severest cases of zinc deficiency, near maximum yields can be produced by plants showing some vegetative symptoms.

Seedlings and plants affected by mild zinc deficiency early in the season, where soil conditions are cool and wet, tend to recover naturally in drier, sunnier conditions of spring.

Treatment

Initial applications of 1 to 2 kg/ha zinc oxide (75% zinc), depending on the soil type, will correct the deficiency. Zinc sulphate and zinc carbonate are suitable

Table 5.5 – Zinc fertilisers and Zn concentration

Source	% zinc
Zinc sulphate heptahydrate	23
Zinc sulphate monohydrate	36
Zinc oxide	78
Zinc carbonate	50-56
Zinc oxy-sulphates	15-45
Chelates	
Zinc EDTA	8-14
Zinc HEDTA	6-10
Zinc NTA	9-13

■ ZINC *(continued)*

alternative sources to zinc oxide. However, the level must be adjusted to apply the same amount of zinc as supplied by zinc oxide. Evenness of application is important.

A foliage spray of 1 kg/ha zinc sulphate (23% zinc) in 50 to 100 litres of water applied as soon as zinc deficiency is detected will prevent its development and reduce grain yield losses. Late foliage sprays of zinc applied to crops, which are recovering naturally in drier, sunnier conditions, may provide little additional benefit.

An annual application of phosphatic fertilisers containing 400 ppm zinc or more is important in maintaining adequate zinc levels in soils. Locally produced phosphatic fertilisers except plain superphosphate all contain 600 ppm zinc.

Residual effectiveness

Zinc has a significant residual effectiveness (that is, the initial application of zinc fertiliser influences the growth and yield of subsequent crops and pastures), therefore, it is not necessary to apply zinc to crops every year. The residual effectiveness depends on the soil type, losses from the system (grain, animal product removal), additions to the system (impurities in fertilisers) and sorption reactions with the soil.

Superphosphate, with 400 to 600 mg/kg Zn has provided adequate zinc for wheat crops decades after the initial zinc application at the development of the soils from virgin scrub. Experiments have shown that on sandy and gravelly wheatbelt soils, an initial application of about 1 kg zinc/ha generally prevents deficiency for at least 16 years if DAP with low zinc concentration is used. There is little knowledge of the residual effectiveness on the fine textured soils which occasionally produce zinc deficiency in wheat.

Herbicides from the sulfonyl-urea and 'FOP' groups induce zinc deficiency in wheat where the soil has a marginal supply of zinc.

Soil and tissue levels

Tissue tests for zinc can be useful in assessing the zinc status of wheat crops, particularly before the head has started to run up into the boot.

Whole tops are sampled, avoiding contact with any zinc-containing or galvanised material. Samples should not be washed in water from galvanised roofs or tanks, or from scheme water.

Plant tops containing less than 12 ppm zinc are noticeably zinc deficiency. Some visual and/or growth effects have been recorded in wheat containing 12 to 16 ppm zinc while levels of 20 ppm or more are normal.

The youngest emerged blade (YEB) is useful as a plant tissue test in diagnosing zinc deficiency in wheat plants before flowering.

Plants containing less than 10 ppm zinc in the YEB are zinc deficient while some visual symptoms and growth effects have been recorded with zinc levels between 10 to 14 ppm. Zinc levels of 15 ppm or more in this tissue indicate an adequate supply of zinc.

Zinc concentration in:		Interpretation
Plant tops	YEB	
< 12	< 12	Noticeably deficient
12-16	10-14	Visual and growth/ effects measured
> 18	> 15	Adequate

Soil tests

DTPA soil extractable zinc closely mirrored the growth of wheat plants or individual soils but the relationship varied markedly between soils. That is, the critical level of soil extractable zinc for wheat plant growth varied between soils of varying soil texture. The fine textured alkaline soil had considerably higher (about 4-5 times) critical level than the acidic sandy soils. The differences in the critical levels of DTPA soil extractable zinc could be accounted for considering the pH, clay content and organic carbon concentration of the soil.

For wheat the critical DTPA extractable zinc (mg/kg) was:

Critical DTPA zinc = 004 + 0.019 pH + 0.004 OC + 0.003 clay

where: pH = soil pH measured in 0.01 m calcium chloride

OC = percentage organic carbon, clay = clay content (%) of the soil.

For example, an acid sand (pH 5, OC 1%, clay 3%) the DTPA soil extractable critical value would be about 0.15 mg/kg zinc while a alkaline sand (pH 8, OC 1%, clay 3%) would be 0.21.

Alkaline (pH > 7.5) clay soils (clay % > 40%) are found to have a critical level of DTPA extractable zinc of about 0.45 mg/kg.

Zinc in grain

The concentration of zinc in grain can be used with limited ability to assess the zinc status of crops, but unfortunately it only diagnoses past problems (post mortem diagnosis).

However, it may identify sites/soils where future crops will respond to applications of zinc fertilisers. Within Western Australia, extensive research trials have found that critical concentration in grain of wheat is about 10 mg/kg. However, this can often be misleading as zinc deficiency causes tillers to die and the zinc that is available to wheat plants can be transferred to grains (to a smaller sink) and filled to adequate or near adequate levels of zinc.

Generally, low zinc levels in grain would be associated with concentrations less than 12 mg zinc/kg for wheat.

MANGANESE

R.F. Brennan

Manganese was the first micronutrient deficiency identified in broadscale agriculture in Western Australia when it was associated with the 'grey speck' disease of oats and wheat. Although manganese deficiency in cereals is widely distributed throughout the south-west of Western Australia, it is usually confined to irregular, well-defined patches rarely exceeding 20 ha. With severe deficiency, grain losses may exceed $200/ha.

Manganese in wheat

Manganese has a role in many metabolic processes and chlorophyll production. The complete role of manganese is not fully understood, however, it is present in chloroplasts and it is also involved as a co-factor of many enzymes (e.g. decarboxylases, dehydrogenase).

Manganese is absorbed as the Mn^{+2} and in deficient plants manganese is relatively immobile and little is translocated from older tissue to growing points. Wheat appears to be intermediately susceptible to manganese deficiency with oats more susceptible and barley less susceptible.

The main regions of manganese deficiency in cereals in Western Australia include:

- The south-western edge of the wheatbelt: from the gravelly white gum country south of Moora and New Norcia, through the powder-bark wandoo and brown mallet country of West Brookton, Wandering, Narrogin, Katanning and east to the gravelly, fluffy red morrel, blue mallet and blue mallee country of Dumbleyung, Moulyinning, Kukerin, Kulin and Corrigin. Patches of manganese deficiency are seen every year in this region.
- The narrow discontinuous coastal strip of lime-sands from west of Northampton to Israelite Bay. Patches of manganese deficiency occur every year.
- South Jerramungup and Esperance Plains where manganese deficiency is seen in drier periods, often on broad, gently sloping, mallee soils.
- Minor occurrences of manganese deficiency in cereals have been seen throughout the remainder of the south-west, usually on gravelly soils on erosion surfaces or on deep, leached, sometimes peaty, sands.

Cereals have appeared little affected by manganese deficiency on the deep grey sand where the manganese deficiency 'split seed' disorder has devastated narrow-leaved lupin (*Lupinus angustifolius*) crops.

Manganese in the soil

Divalent manganese (Mn^{+2}) is absorbed by clay minerals and organic matter and is the most important manganese ion in the soil solution for plant nutrition.

Manganese participates in many soil reactions, including oxidation and reduction, ion exchange, specific adsorption and solubility equilibrium. As Mn^{+2} level in the soil depends on oxidation-reduction reactions, all factors which influence these processes have impact on manganese availability to wheat plants. These include soil pH, organic matter, microbial activity and soil moisture. The availability of manganese increases with increasing soil moisture and declines with increasing soil pH.

Symptoms

Seedlings of wheat usually grow normally until about early tillering in the gravels and mallee soils, but earlier effects of manganese deficiency have been seen on lime-sands. Pale yellow-green patches with irregular but clearly defined edges develop in the crop. These become paler as the season develops and the wheat plants tend to wilt and droop in warmer weather although soil moisture is adequate.

All the leaves of wheat, oats and barley become pale but symptoms show first on older leaves before extending to newer growth. The pale leaves become limp and soft, eventually dying, producing a dead and wilted basal flag leaf. A very weak head may be produced, or none at all if the plant dies prematurely from severe deficiency of manganese.

Copper deficiency can produce similar symptoms but usually in copper deficiency the older leaves are darker green than the younger leaves.

Manganese deficiency can often be mistaken for the fungal root disease take-all *(Guanomyces tritici)* except that oats are immune to the fungus. Manganese deficiency usually occurs each year in definite patches of characteristic soils, although this may not be true of lime-sands.

Plant tissue levels

In whole tops of wheat, a manganese level below 20 ppm indicates a possible problem and below 10 ppm indicates almost certain deficiency. In youngest emerged leaf blades a level of 12 ppm would indicate manganese deficiency.

Spraying foliar manganese in strips across the crop can check indications gained from tissue analysis.

Soil testing

There will probably never be a reliable soil test for manganese. This is because the concentration of manganese as the Mn^{+2} in the soil solution can vary by orders of magnitude within short periods of time with fluctuating soil conditions (e.g. soil moisture).

The soil test is regarded as no more than a rough guide. The top 10 cm of problem soils usually contain < 2 mg/kg of manganese extractable in hydroxyquinone or < 0.5 mg manganese/kg that can be extracted in 1 M ammonium acetate. Soil test for DTPA extractable manganese in the soil have not been studied in soils of Western Australia.

■ MANGANESE *(continued)*

Manganese concentration in grain

Manganese concentration in the grain of about 15 mg/kg can be a diagnostic tool for manganese deficiency of wheat, but suffers by being retrospective. It can, however, be misleading as during maturation retranslocation of manganese from vegetative plant tissue, or from greater manganese availability late in the season from the soil as soil temperatures increase (provided there is adequate soil moisture), manganese can reach adequate levels in the grain.

A retrospective diagnosis of Mn by grain analysis has not been extensively used in Western Australia or Australia wheat growing districts.

Treatment

Manganese deficiency is controlled by:

- mixing manganese sulphate with superphosphate and drilling it with the seed;
- spraying leaves with manganese sulphate; or proprietary products cotaining plant available manganese for foliar application;
- drilling ammonium sulphate fertilisers (such as Agras) with the wheat seed.

Manganese sulphate and superphosphate

On all soils, except highly alkaline soils (e.g. coastal lime sands), 15 kg/ha manganese sulphate (fertiliser grade) mixed with superphosphate drilled with the seed gives profitable grain increases in all cases. Some manganese deficiency may still develop in the most deficient situations.

Topdressed manganese sulphate is usually only half as effective as drilling it with the seed – so twice as much manganese fertiliser is needed. Coarse-granulated manganese sulphate is markedly less efficient than fine particles or powder, particularly in dry conditions.

Manganese-superphosphate is most profitable where manganese deficiency is known to occur in patches every season.

Table 5.6 – Manganese fertiliser and their Mn concentration

Source	% manganese
Manganese sulphate	26-30
Manganese oxides	41-68
Manganese chelate	12
Manganese carbonate	31
Manganese chloride	17

Foliar sprays

Manganese sulphate (spray grade) at 4 kg/ha in 100 L/ha water is usually very effective on cereals when applied immediately the symptoms show and before plant growth is retarded. Best results are obtained in cool, moist or dewy conditions of early morning or late evening. Two sprays may be needed three weeks apart for complete control of the deficiency in wheat plants.

Foliage sprays are useful for treating the usually scattered manganese deficient areas, where the deficiency is noticed for the first time, or on areas where the deficiency occurs in some seasons but not others. It is also useful where manganese superphosphate or ammonium sulphate drilled with the seed has not fully prevented Mn deficiency of wheat.

Spray-grade manganese sulphate, free of impurities, is usually available at a higher price then fertiliser grade. A range of commercial products are available (for example, manganasol®, mantrac®) and are recommended to be sprayed at comparable amounts of manganese as that applied in maganese sulphate.

Ammonium sulphate

Acid-forming nitrogenous fertilisers increase the plant availability of any reactive manganese in the soil. Ammonium sulphate, alone or as a component of Agras, and ammonium nitrate, have markedly reduced manganese deficiency of wheat.

Ammonium sulphate often eliminates manganese deficiency or reduces it to patches that can be spot-sprayed. Drilling Agras at 100 kg/ha or more reduces the risk of irreversible growth retardation before a spray can be applied and saves wasting manganese-superphosphate on non-deficient areas. Agras applied at > 130-150 kg/ha germination of wheat seedling may be effected, but is strongly influenced by soil moisture and rainfall events following the high levels of Agras used.

Ammonium sulphate based fertilisers are best choice for country prone to manganese deficiency and where there is no way of establishing the location of manganese deficient patches of wheat.

Increased yields in response to the nitrogen content usually more than pay for the Agras even where there is no manganese deficiency.

Role of manganese nutrition and take-all

Manganese has been reported to decrease the severity of take-all. However, the effectiveness of manganese fertiliser for reducing take-all depends on the method of application. Manganese sulphate spread over the soil surface before sowing (topdressed or broadcasted) had little effect in decreasing take-all. Whilst manganese sulphate placed with the seed (drilled or banded with the seed) while sowing wheat was only partly effective because there was limited distribution of manganese around the roots of the wheat plants. Work done in Western Australia, suggested that take-all is more severe where plants are deficient in manganese. However, there were no beneficial effects of applied manganese if the wheat plants were adequately supplied with soil manganese.

■ MOLYBDENUM

R.F. Brennan

Western Australia has vast areas of highly weathered acidic soils where the native levels of plant available molybdenum are extremely low for the maximum growth and yield of wheat.

Molybdenum in plants

All plants require molybdenum where nitrogen is absorbed as the nitrate form because molybdenum is a critical component of the nitrate reductase enzyme. In cereals, molybdenum is required for grain formation, as impaired or incomplete grain filling is observed in molybdenum deficient wheat plants. The heads of molybdenum deficient wheat are often barren of grain or contain shrivelled grain. The heads produced are often called 'deaf ears' or white heads. This is a non-specific symptom of molybdenum deficiency in wheat as it could often be confused with copper deficiency.

Molybdenum is less soluble in acidic soils, and molybdenum is more strongly adsorbed by soils as the soils become acidic. Therfore, molybdenum concentrations in soil solution decrease as soils are more acidic or acidify, thereby inducing deficiency in wheat. So deficiency is not observed in alkaline soils, and it becomes more prevalent as soils are more acidic, or acidify due to acidification caused by productive agriculture. Results in Western Australia show that grain yield reductions in wheat due to molybdenum deficiency are accentuated when ammonium sulphate is applied. This is probably because ammonium sulphate is acidic, and when it is drilled with wheat seed at sowing, the region of soil in the band drilled with the seed becomes more acidic, so there is less molybdenum in soil solution.

Molybdenum deficiency in wheat is restricted to the acidic members of the yellow-brown lateritic earthy sands and sandy earths of the south-central, central, eastern, northern and north-eastern wheatbelt – where the pH (in-water) of the top 10 cm is less than 6.

About half of the 3 million hectares of these soils are molybdenum deficient immediately after clearing but molybdenum deficiency is almost certain to develop on the remainder as soil acidity increases.

The acid yellow sandy earths vary considerably in soil pH, clay and iron and aluminium sesquioxide concentration, which are important soil factors in determining molybdenum availability to wheat plants. The acid yellow sandy earths are commonly known as 'wodgil' soils because of the vegetation is often dominated by tammar (*Casuaria campestries*), mallee (*Eucalyptus burracoppinensis*), flame grevillea (*Grevillea excelsior*), Acacia spp. and quandong (*Santalum acuminatum*).

Molybdenum in the soil

If there is little Mo available for wheat uptake, it may be because the total content is low in the soil, or there is a low concentration of molybdenum in the soil solution due to adsorption of molybdate to soil surfaces and the formation of discrete, secondary compounds.

Soil pH and the iron and aluminium sesquioxides contents of soils have a significant effect on molybdenum availability to wheat plants.

(i) Soil pH. The addition of lime increasing the soil pH resulting in an increased uptake of molybdenum by wheat.

(ii) Iron and aluminium. Iron and aluminium as free ions, colloids or coatings on soil constituents offer major sites for adsorption and are a major factor in determining molybdenum availability to wheat plants in soils.

Symptoms

Molybdenum deficiency can decrease wheat yield by up to 30% before symptoms are seen.

As molybdenum plays a vital role in the nitrogen metabolism of wheat plants, deficiency initially expresses itself as a nitrogen deficiency.

The major symptoms of nitrogen deficiency are:

- reduced tillering, foliage and shortened internodes; and
- plants generally paler (confused with manganese and copper deficiencies).

In most severe cases, symptoms specific to molybdenum deficiency are:

- Delayed maturity, often occurring with empty heads – can be confused with copper deficiency, root rots, frost or drought.
- Severely affected plants may die, yet can often occur near healthy, individual plants. It can be confused with copper deficiency or root rots.
- A symptom, which has been observed in the glasshouse in young wheat plants, is white, necrotic areas extending back along the leaves from the tips. It can be confused with copper deficiency or herbicide damage.

Treatment

The methods of applying molybdenum to crops include application of molybdenum fertiliser to the soil, coating the seed with molybdenum compounds or applying molybdenum to crops as a foliar spray.

Molybdenum deficiency can be corrected by using a molybdenum added to superphosphate during manufacture. The recommended level of molybdenum application for soil application in Western Australia is 75 g of molybdenum/ha.

Molybdenum can be applied in several ways:

sodium molybdate (39% molybdenum), ammonium molybdate (54% molybdenum) and molybdenum trioxide (66% molybdenum). Molybdenum trioxide is least soluble of the sources but appears to be equally effective for plant

MOLYBDENUM *(continued)*

uptate and has similar residual effects. Molybdenite (MoS_2, 60% molybdenum) has a low solubility and has been found to be ineffective for plant update.

Applications of molybdenum as a foliar spray or as a seed treatment can be more effective than a soil application, but it needs to be added to each crop.

Molybdenum can be sprayed on foliage. Use 50 g sodium molybdate (39.6% molybdenum grade) in 50 to 100 litres of water per hectare, which gives 20 g/ha of molybdenum. Although this is about one-quarter of the rate recommended for soil application, foliage application is not generally recommended because re-application is needed regularly and because of the molybdenosis risk. There is a range of molybdenum spray products that are available and should be used at the same molybdenum level and compared on price.

Residual value

While application of molybdenum is recommended on new land, little is known about the need for re-application, as information about the residual value of molybdenum is scarce.

The availability of molybdenum declines at different rates for different soil types, depending mainly on their acidity and content of iron and aluminium oxides.

Soils that have a pH above 5.5 (in water) (about 4.5 in calcium chloride) in the top 10 cm a single application of 75 g/ha molybdenum as fertiliser applied to the soil has remained effective for 15 years or more.

However, on some yellow-brown sandplain soils of the central and north-eastern wheatbelt, where the surface pH has been below 5.5 (less than about 4.5 in calcium chloride), and the pH of the 10 to 20 cm layer has been 4.5 or lower (3.9 in calcium chloride), the effectiveness of molybdenum fertiliser applied to the soil has declined rapidly over two to three years.

The need for molybdenum fertiliser should be checked by tissue analysis or by test strips of the superphosphate-molybdenum mix compared with plain superphosphate (with no added molybdenum) applied at the same rate and on the same day.

The requirement for re-application of molybdenum can be minimised by using seed taken from 'high fertility' paddocks (i.e. those with adequate molybdenum levels), and avoid seed from highly acidic paddocks or where ammonium sulphate based fertilisers are used.

Tissue tests

A plant test can diagnose molybdenum deficiency in wheat at the time of sampling. The critical concentration of molybdenum in the youngest fully emerged leaf appears to lie between 30 and 50 mg/g (0.03 and 0.05 mg/kg). However, the tissue tests for molybdenum are expensive and few laboratories can analyse the small samples of plant material accurately enough for this diagnosis.

Soil test

There is currently no soil test available for identifying molybdenum deficient soil.

Molybdenum in grain

The concentration of molybdenum in wheat grain has some use as to indicate if molybdenum status of the soil is low. However, grain analysis is limited in that the reduced number of grains through molybdenum deficiency can result in grain with adequate moybdenum levels. Marginal molybdenum levels in grain have been tentatively set at 0.1 mg molybdenum/kg.

■ BORON

M.M. Riley, revised by R.F. Brennan

Boron deficiency has been reported in eastern Australia, but is rare in Western Australia, and the few isolated cases have usually been associated with lime application. However, boron toxicity of wheat (and barley) has been of concern in the lower rainfall areas of Western Australia.

Background

In Western Australia, the land surface has been stable for a long period in recent geologic history, with large areas of uncoordinated drainage, large inputs of cyclic salt, and high evaporation. The association of these factors has resulted in the saline groundwaters and surface waters and saline or sodic soils which are problems in much of the south-west of the State, particularly eastwards of the 550 mm rainfall isohyet. These semi-arid conditions are also favourable for the accumulation of boron in the soil profile.

In general, both total and water-soluble boron can be high in arid and semi-arid areas in which boron has naturally accumulated and leaching is limited. In these areas boron in the subsoil often exceeds that in surface soils. Boron in such soils often exists as sodium or calcium salts, and is usually found at toxic levels in saline and sodic soils. The alkaline, sodic soils associated with boron toxicity in South Australia are also widespread in the medium to low rainfall areas of Western Australia where boron toxicity has been reported. However, the incidence of boron toxicity in wheat and barley appears higher in salt-lake areas, particularly in the south-eastern zone of the south-west land division.

Symptoms of boron toxicity

General

In a study of boron toxicity in a number of plant species, it was observed that the pattern of toxicity was related to type of leaf venation. Generally, however, the symptoms of boron toxicity are similar on most plants, consisting primarily of chlorosis and subsequent necrosis of margin and tip portions of leaves. Boron is concentrated in the relatively small necrotic areas near the leaf tips and margins.

Accumulation of boron in relatively small necrotic areas provides a possible explanation for the observations that yield decreases associated with boron toxicity are often small.

Cereals

In barley, foliar symptoms characteristic of boron toxicity have been reported in a number of studies and appear similar for a wide range of barley genotypes.

Genotypic variation

As soil amelioration appears unfeasible, focus has centred on the exploitation of genetic variation in tolerance as a possible solution to boron toxicity. Cereals are generally ranked as semi-tolerant to boron excess, with relative ranking of barley, wheat and oats differing between studies. It is evident from the contradictory rankings reported in previous studies, that variation among genotypes of a cereal species (i.e. intraspecific variation) may be as large as the variation between cereal species (i.e. interspecific variation) in tolerance to boron excess.

Research work in Western Australia has shown that variation in tolerance to boron toxicity was found to exist among the cereal genotypes. The results suggested that intraspecific variation might be as large as interspecific variation among cereal genotypes in tolerance to boron toxicity. For example, Eradu wheat and Stirling barley appeared to be the least tolerant of high levels of soil boron, while Mortlock oats were the most tolerant.

The relatively high tolerance of Halberd wheat was derived from its ability to exclude boron, particularly at high levels of soil boron. The internal tolerance to boron of Halberd relative to Eradu wheat was not constant over the concentration range examined. The critical toxicity concentration (CTC) (associated with a 10% reduction in the dry weight of whole shoots) determined for Halberd was markedly lower than for Eradu. If, however, CTC values were determined at levels associated with 30% reductions in the dry weights of whole shoot, the value for Halberd would be markedly higher than for Eradu.

Symptoms of leaf injury from boron toxicity were marked in all the cereal genotypes before the dry weights of whole shoot were decreased. Although the symptoms of dark necrotic spotting were not evident, the wheat and oat genotypes were similar to the barley genotypes in that larger amounts of leaf area from the tips and margins became necrotic with increasing boron toxicity.

The findings of experimental work have important implications for evaluating cereal genotypes for tolerance to boron toxicity in the field. They indicate that the relationship between concentrations of boron in whole shoots, ratings of leaf injury, and plant growth are not consistent between genotypes.

The ranking of wheat and barley genotypes by ratings of leaf injury has limitations, as the relationship between ratings and yield loss is not consistent among genotypes. Generally, however, the genotypes with relatively higher tolerances to boron toxicity had lower ratings of leaf injury at both a given level of soil boron or a given concentration of boron within the whole shoot.

Among wheat genotypes, the grain yield of Halberd has been shown to be relatively higher on soils with 'toxic' than 'normal' levels of boron. As Halberd has been shown to accumulate relatively lower amounts of boron in the grain, it has been suggested that Halberd is relatively more tolerant (based upon exclusion) of excess boron in soils. However, no statistical relationship has been found between the yields of genotypes of wheat and the concentrations of boron in the whole shoots or grain.

■ BORON *(continued)*

Similar results among wheat genotypes have been observed in field experiments in Western Australia.

Cereal genotypes tolerant of boron toxicity can only be selected, therefore, by evaluating effects on growth.

Assessment

(a) Leaf symptoms are the simplest method of identifying boron toxicity, but even when symptoms are present, it is almost impossible to accurately gauge the effects on grain yield.

(b) Soil testing can identify high concentration of boron in the subsoil and therefore soils with a potential to cause problems in wheat (and barley). A range of soil chemical extractants have been used, such as mannitol, hot water and hot calcium chloride; hot calcium chloride is the now preferred extractant. Soils with boron values of more than 20 mg/kg by the hot calcium chloride method could cause boron toxicity problems.

(c) Plant tissue or grain analysis is of limited value in identifying whether grain yields are reduced, although the grain concentration can be used to identify potential problem soils. If the grain concentration is 3 mg/kg or higher, then the crop was grown on soil with a potential to develop toxicity problems.

NUTRIENT REMOVAL IN WHEAT CROP PRODUCTS

J.W. Gartrell and M.D.A. Bolland

Nutrient concentrations in wheat plants and their different parts vary greatly depending on season, management practices, available soil nutrient levels and variety. The ranges of the amount of nutrients commonly found in wheat grain and straw in Western Australian crops are shown in Table 5.7.

The amounts of nutrients removed in one tonne of 'typical' grain, straw-stubble left after harvesting grain, and hay, and the cost of fertilisers which would replace them, are shown in Table 5.8.

Maintenance

To maintain the level of plant-available nutrients in the soil in successive wheat cropping systems, more nutrients must be applied than is removed in wheat grain or other products. This is to compensate for losses other than in crop products.

The nature and extent of other losses vary between nutrients, soil properties and the amount and seasonal distribution of rainfall.

The burning of cereal stubble causes little or no direct loss of plant-available nutrients. However, important quantities of nutrients may be lost if burning the stubble allows severe wind erosion that would not otherwise have occurred.

Nitrogen

Nitrogen is most prone to losses by biological processes and leaching. Commonly the amount of fertiliser nitrogen needed to maintain fertility is double the amount of nitrogen removed in crop products.

In rotations of wheat with legumes the legumes may, for little or no cost, add more nitrogen to the soil than that removed in crop products.

Phosphorus

Phosphorus is most prone to losses in solubility caused by chemical reactions (known as fixation, reversion, adsorption, sorption, retention). Phosphorus mostly leaches out of pale, coarse sands with high rainfall.

Losses of phosphorus by fixation in our soils are in the range of 2 to 10 kg of phosphorus per hectare per year, with about 4 kg/ha phosphorus being most common.

Periodic applications of superphosphate are usually needed to replace the calcium and sulphur removed in crop products.

Potassium

Potassium is prone to leaching on soils low in clays and organic matter with high rainfall. Only on very sandy soils in the wetter parts of the wheatbelt are potassium losses by leaching likely to be significant.

Potassium removal in one tonne of hay or stubble is much higher than in one tonne of grain. Many of our sandy soils have low reserves of plant-available potassium.

The need to replace potassium removed in crop products will become increasingly common, particularly where straw or hay is repeatedly removed from the paddock.

Trace elements

The amounts of trace elements removed in crop products have a negligible effect on their supply, in plant-available form, in soils.

The needs for application or re-application of the trace elements are almost entirely governed by processes other than product removal, such as soil acidity.

Most Western Australian soils have large reserves of plant-available magnesium. Magnesium deficiency rarely occurs in the wheatbelt.

Table 5.7. – The range of nutrients in wheat grain and straw found in Western Australian crops.

In one tonne of	Mineral element content (kg)								
	N	P	K	S	Mg	Ca	Cu	Zn	Mn
Grain	16 to 26	2 to 3.5	3 to 7	2 to 3	1 to 1.5	0.2 to 0.4	0.002 to 0.004	0.1 to 0.30	0.01 to 0.05
Straw	2 to 10	0.2 to 1.5	6 to 16	0.4 to 1.5	0.5 to 1	0.6 to 2	0.001 to 0.003	0.01 to 0.03	0.01 to 0.06

N = nitrogen; P = phosphorus; K = potassium; S = sulphur; Mg = magnesium; Ca = calcium; Cu = copper; Zn = zinc; Mn = manganese.

■ NUTRIENT REMOVAL IN WHEAT CROP PRODUCTS *(continued)*

Table 5.8 – Cost of replacing nutrients removed in 1 tonne of produce with 'typical' nutrient levels, using an appropriate type of fertiliser (1990 price). Costs of trace elements removed are negligible

Nutrient element	Amount in 1 tonne of product	Fertiliser		Approximate cost 150 km from Perth ($)
		Type	Rate (kg/ha)	
	Grain (kg)			
N	20	Urea	43	(a) 14.60
P	2.5	OSP†	2705	5.00
K	4	KCI††	8	2.70
S	3	Supplied by OSP		Nil
Mg	1	Dolomite	7	0.40
Ca	0.3	Supplied by OSP		Nil
	Straw (kg)			
N	5	Urea	11	(a) 3.70
P	0.5	OSP†	5.0	1.00
K	10	KCI††	20	6.60
S	0.5	Supplied by OSP		Nil
Mg	0.7	Dolomite	5	0.25
Ca	1	Supplied by OSP		Nil
	Hay (soft dough stage)			
N	16	Urea	34.5	(a) 11.70
P	2.1	OSP†	23	4.20
K	12	KCI††	24	7.90
S	1.5	Supplied by OSP		Nil
Mg	1	Dolomite	7	0.40
Ca	1	Supplied by OSP		Nil

† OSP = Ordinary superphosphate (9.1% P).
†† KC1 = Muriate of potash.
Note: (a) Cost of nitrogen may be zero if legumes are profitably grown in rotation with wheat.

CHAPTER SIX

WHEAT IN FARMING SYSTEMS

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■ WHEAT IN FARMING SYSTEMS

Wheat production is a prominent and common land use on many Western Australian farms. Wheat crops fit well among other farming enterprises and they highlight the benefits of growing cereal crops in rotation with other species.

Rotations have commonly been defined as:

"the growing of crops and/or pastures in a fixed sequence with the aim of *maximising the long term productivity and profitability* of the farm".

In fact, this concept of rotation is proving to be too restrictive because economic and technological changes are occurring so fast that land use sequences are not necessarily repeated in a fixed sequence. However, the concept of using a range of species, particularly crop and pasture legumes, between cereal crops remains a central element of our farming system and these sequences loosely fit the concept of rotation. The opposite of rotation is continuous cropping of a single species which with cereals, is considered exploitative of the environment and eventually detrimental to profitability.

Usually the rotation sequence includes wheat or another cereal crop grown in rotation with a broadleaved (non-cereal) plant. The common broad-leaved plants are pasture, grain legumes and Brassica species such as canola. The benefits of rotation versus continuous cereal cropping (or fallow/crop) are due to:

- improvements in fertility: nitrogen (legumes only);
  – recycling of nutrients, for example potassium;
  – improvement of soil structure;
- complementary soil water use, (as one phase of the rotation may leave water stored for use by a subsequent crop);
- reduced depletion of soil organic matter and degradation of soil structure (Hamblin and Kyneur 1993);
- integrated weed management: improved options for controlling weeds through the use of herbicides of a different herbicide family as well as grazing and other cultural methods such as green manuring;
- disease control through breaking of disease cycles;
- pest control: insect pests such as webworm, desiantha, and cereal cyst nematode can be controlled in rotation;
- better use of capital equipment and labour may be possible if the components of the rotation are not competitive in their requirements; and
- diversification of sources of income: particularly where pastures and livestock production form an important part of the farm system.

■ ROTATION TYPES

Ley farming

In the past, wheatbelt pasture legumes in Western Australia were mainly subterranean clover (*Trifolium subterraneum*), species of annual medics (*Medicago*) and more recently, serradella (*Ornithopus compressus*). These species were chosen in part for their adaptation to common soil types but also for their ability to naturally regenerate, following cropping, from seed reserves in the soil. These legume-based pastures were sown once and were capable of surviving one or two years of crop before regenerating to form a legume dominant pasture. The sustainability of this system, commonly called the ley farming system, has been challenged by the adoption of longer cropping sequences which now occur following the wide scale adoption of pulses (lupins, faba beans, chickpea, field pea and lentils) and oilseed crops (canola). The seed pool of the annual pasture legume is unable to survive in sufficient numbers during the extended cropping phase, to produce a legume dominant pasture. Self-regenerating pasture rotations remain a particularly important rotational option in situations where the profitability of pulses is poor due to low or unreliable yields, but where a pasture legume can persist as part of an intensively cropped system.

All crop systems

The development of pulse and oilseed crops have allowed the emergence of systems that have a strong emphasis on crop production while preserving most of the rotational benefits previously obtained with self-regenerating pastures. Such systems also avoid the problems of long term cereal monoculture. While simple rotations involving wheat and lupins have been a prominent and profitable land use in Western Australia in the 1980s and 1990s, there are doubts now about their long-term sustainability. Heavy reliance on a narrow spectrum of weed control strategies, particularly for selective herbicides, has led to the emergence of herbicide resistant weeds which now threaten the profitability and sustainability of such systems. The inclusion of canola into such rotations is helpful in providing an opportunity for contrasting weed control strategies to be adopted, and to reduce disease threats by increasing the grow-back time between crop species. However, further increases in rotational complexity are desirable, particularly the option of a pasture phase.

Phase crop / pasture systems

'Phase farming' is a modification of ley farming but with much less connection between the crop and livestock enterprise at the paddock level (Reeves and Ewing, 1993). In the context of pastures, short term phases (one to three years of pasture) are used to break up long cropping sequences, restore soil fertility and control troublesome weeds. The length of the cropping sequences are such that pastures are unable to regenerate without intervention. For annual pastures, resowing at the start of each pasture phase is therefore required. Under these circumstances the high level of hard seed necessary to ensure persistence through a cropping phase becomes unnecessary and may actually inhibit dense regeneration in the years following establishment. Plant characteristics for annual 'phase' pasture species are quite different from traditional self-regenerating species and include

- low to moderate levels of hard seed;
- adaptation to soils where intensive cropping is practised;
- compatibility with the use of non-selective herbicides for weed control;
- ability to fix nitrogen despite a build up in soil fertility;
- ability to compete with volunteer species under a wide range of grazing regimes; and
- low seed cost because of the need for frequent resowing and to encourage high seeding rates.

Aerial seeding of pasture legume species (for example, French serradella) is now being developed for 'phase' pasture systems which can be directly harvested with cereal harvesting technology to reduce the cost of seed. Expanded opportunities for weed control arise in a phase pasture system. In the last year of the pasture phase, destructive techniques like mowing, hay freezing, hay cutting, silage making and green manuring are possible since there is no requirement for legume seed production to sustain the system.

'Phased' pastures also lend themselves to the inclusion of perennials in the farming system with the associated benefits of a reduced groundwater recharge and the production of a high quality feed source outside the normal growing season. There are clear advantages for the inclusion of herbaceous perennial legumes such as lucerne in pasture phases of three to four years, followed by a similar period of annual crops. Shrub legumes such as tagasaste may also play an important role in stabilising the hydrological cycle but are more likely to be used in an alley system rather than a 'phase' pasture system.

In the Western Australian wheatbelt, pasture legumes are mainly subterranean clover (*Trifolium subterraneum*); species of annual medics (*Medicago* sp.) and serradella (*Ornithopus* sp.), although many new species are now being commercialised. The main grain legumes are the narrow leaved lupin (*Lupinus angustifolius*), desi chickpea (*Cicer arietinum*), field pea (*Pisum sativuam*), faba bean (*Vicia faba*), lentil (*Lens culinaris*) and vetches (*Vicia* sp.). Common legume species and their favoured soil types are listed in Table 6.1.

■ ROTATION TYPES *(continued)*

Table 6.1 – Legume species of the Western Australian wheatbelt

Plant Species		**Soil Types**
Subterranean Clover	*Trifolium subterraneum*	Acid to neutral loams and sands
Balansa clover	*Trifolium michelanium*	Wet sandy loams to clay loams
Barrel medic	*Medicago truncatula*	Alkaline heavy clay loams
Strand Medic	*Medicago littoralis*	Neutral to alkaline sandy soils
Sphere medic	*Medicago sphaerocarpos*	Mildly acidic sandy loams and loams
Burr medic	*Medicago polymorpha*	Slightly acid to heavy grey clays, loams and sandy loams and on neutral to alkaline heavy red soils
Yellow serradella	*Ornithopus compressus*	Acidic deep sands, loamy sands
French serradella	*Ornithopus sativus*	Acidic deep sands, loamy sands
Biserrula	*Biserrula pelecinus*	Acid to neutral sands and loams
Lucerne	*Medicago sativus*	Mildly acidic loams and sandy loams and on neutral to alkaline heavy red soils
Narrow-leaved lupin	*Lupinus angustifolius*	Acidic to neutral deep sands, sandy loams and deep duplex soils.
Field Pea	*Pisum sativum*	Slightly acidic loams Neutral to alkaline clay loams and loams
Chickpea	*Cicer arietinum*	Slightly acidic loams to alkaline clay loams. Neutral to alkaline loams and clay loams.
Faba Bean	*Vicia faba*	Slightly acidic loams to alkaline clay loams
Lentil	*Lens culinaris*	Neutral to alkaline loams and clay loams
Vetches	Vicia sp	Wide range of soil types pH 4.5 -9.0 in $Cacl_2$

SOIL FERTILITY

The most important feature of legumes is that they have the ability to make or 'fix' their own nitrogen from the air, when effectively nodulated. This 'nitrogen fixation' is achieved by the successful symbiosis of the plant and a bacteria called Rhizobium, found in nodules on the legume's roots. The accumulation, depletion and subsequent cycling of soil nitrogen is the most important interaction in the legume-cereal rotation.

Although grain legumes have been shown to improve soil fertility by increasing the nitrogen status of the soil, the long-term effect of continuous cropping is a general decline in soil fertility and surface structural condition.

Depletion of soil nitrogen

Cereals remove about 18 kg of nitrogen per tonne of grain at 10.3% protein. Burning or grazing of stubbles will cause additional losses, but these are small as little nitrogen remains in mature stubbles (which at 0.2% nitrogen, will contain about 3.8 kg of nitrogen per tonne of grain harvested).

All cereal crops use the nitrogen that is supplied when soil organic matter is mineralised. Mineralisation may be partially balanced by non-symbiotic nitrogen fixation (from other free living soil microbes) and by some incorporation of fertiliser nitrogen into organic matter, but soil nitrogen tends to decrease in continuous cereal cropping.

Accumulation of soil nitrogen

Under undisturbed leguminous pastures, soil nitrogen increases and the quantity of symbiotically fixed nitrogen exceeds the mineralisation of organic nitrogen.

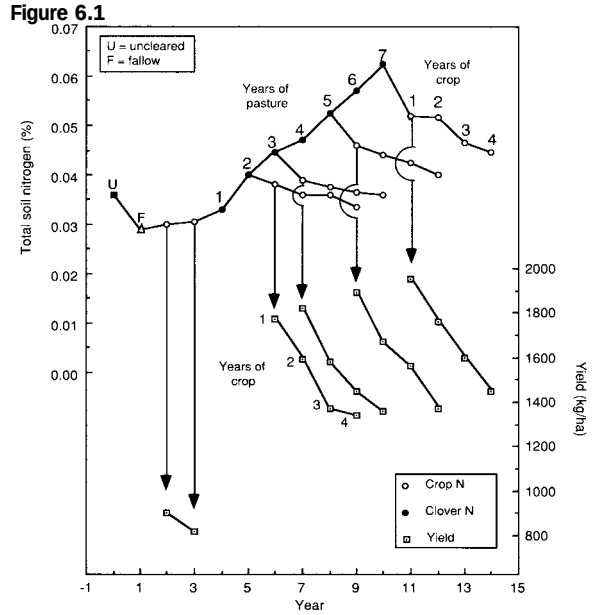
The nitrogen fixed during a legume pasture phase or by a grain legume crop is incorporated into organic matter in the soil. This soil nitrogen does not form a single 'pool', but is present in many different forms depending on its source and age.

Some pools of nitrogen are highly resistant to breakdown. Nitrogen derived from recent inputs of crop and pasture residues can be mineralised rapidly and be a major contributor to subsequent plant growth. For example, about 3% of total organic nitrogen may mineralise over a season, however this may include 40 to 50% of last year's organic nitrogen. Any serious attempt to estimate the value of residual nitrogen for a following crop must account for these differing pools.

Fluctuation in nitrogen levels

Where crop and pasture phases alternate, soil organic nitrogen will fluctuate as in Figure 6.1, where the subterranean clover pasture increased soil nitrogen by about 64 kg/ha/year. This is nitrogen incorporated into organic matter, much of which is not immediately available to a following cereal crop.

Figure 6.1



Soil nitrogen increases under pasture and decreases in crop

Sowing the pastures to wheat caused a rapid decline in total soil nitrogen in the first crop, but only a slow subsequent decline. Wheat yields also increased with increasing length of the preceding pasture phase, but the main effect was seen after the first two years of legume pasture.

Nitrogen balance

Although a great simplification (that is, considering all soil nitrogen as a single pool), the balance between accumulation and depletion of soil nitrogen was formalised in a simple equation by one worker in 1971:

Change in soil N = -kN + a

The change in soil nitrogen is over some period, usually a year; 'k' is a nitrogen loss coefficient for soil organic nitrogen – to account for losses like mineralisation, leaching and volatilization. 'N' is the nitrogen content of the topsoil (say 0 to 10 cm) and 'a' is the accumulation of nitrogen in a specified time for the same volume of soil. The equation says simply that the change in soil nitrogen is equal to the sum of the gains and losses from the pool of soil nitrogen over a year.

For a fallow-wheat rotation in South Australia, 'k' was taken to be 0.04 and 'a' was 20 kg/ha/year. The equation suggests that from 3000 kg/ha of soil nitrogen at the start of cropping, only about 1000 kg/ha remained after 50 years and an eventual new equilibrium, (where gains equal losses), of 500 kg/ha of soil nitrogen was reached.

Introducing legume pastures to a rotation changes both 'a' and 'k'. There have been a considerable number of estimates of nitrogen accumulation under temperate pasture legumes in southern Australia. In a review of N fixation in annual legumes by Unkovich *et al.* (1997), data

■ SOIL FERTILITY *(continued)*

for subterranean clover pastures ranged from 0 to 188 kg/ha/yr N fixed with an average of 92 kg/ha/yr (which did not include N fixed in underground biomass). Precise measurement of k, the decomposition constant, is rare, but values of 0.029 and 0.013 have been measured for two annual pastures. These are much lower values than for a crop where cultivation hastens mineralisation of the organic matter.

Rotations of alternating pasture and crop will accumulate and deplete soil nitrogen around a value which will depend on the length of the pasture phase. For cereal crops, what is important is not the actual levels or trends in total soil nitrogen but the level of mineralisation that will make nitrogen available to the crop.

Assuming that 2% of soil organic matter is mineralised in pasture (k_p=0.02) and 4% for a crop (k_c = 0.04), the equilibrium soil nitrogen levels, and mineralisation on breaking up the pasture are shown in Table 6.2.

Table 6.2 – Effect of rotation on equilibrium and mineralisation levels of soil nitrogen

	Equilibrium soil nitrogen (kg N/ha)	**Mineralisation (kg N/ha)**
Continuous pasture	3,350	134
2 crop : 4 pasture	1,925	77
1 crop : 1 pasture	1450	58
Continuous crop	500	20

In reality, soil nitrogen does not exist as one pool; and the values of 'k' and 'a' change with season, crops and cultural conditions. Nevertheless, the equation demonstrates how the nitrogen flows in a rotation of legume pastures and crops.

Other nutrients

Increases in organic matter under pastures not only store nitrogen, but also phosphorus and sulphur, which might otherwise be leached or bound to soil minerals. Cation exchange capacity is also increased which assists in retaining nutrients such as potassium and manganese.

Effect of legumes on soil nitrogen

Grain legume crops do not derive their entire N from fixation as some N is taken up from the soil. The N fixation process is 'metabolically expensive'; requiring energy that could otherwise be used for growth. So legumes tend to use soil N in preference to fixed N, especially if there is a large amount of soil N available.

The proportion of crop N derived from fixation depends on:

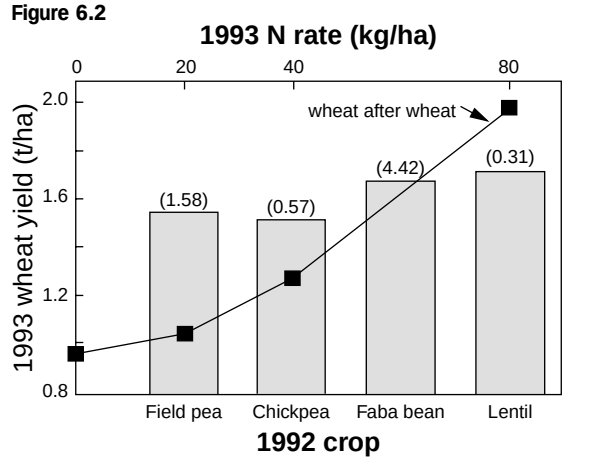
- availability of soil N – nitrate in the soil suppresses nodulation and N fixation and legume crops use more soil N where soil N levels are high (Jessop and Mahoney 1985)
- crop N demand – crops growing vigorously require more N than poor crops, so will derive a greater proportion of their N from fixation
- legume species – faba bean and lupin appear to fix more N than field pea and chickpea

The amount of N that is left for following crops also depends on the partitioning of N within the legume crop. One of the aims of growers and agronomists is to improve seed yields; increasing yields involves the removal of large amounts of N in the harvested grain. In some cases, usually where soil N contents are high, more N is removed in the seed than the crop actually fixes from the atmosphere. This results in a depletion of soil N (Unkovich et al. 1997, Schwenke and Herridge 1998).

Grain legume crops may also enhance N supply to subsequent crops through 'N sparing' (Herridge et al. 1995). Nitrate levels in the root zone of legume crops are usually higher than in the root zone of non-legume crops. It has been proposed that legumes place less demand on soil N than other crops, due to their ability to fix atmospheric N, allowing it to accumulate as it is released from soil organic matter.

Some researchers dispute this interpretation, claiming that the elevated nitrate levels are due to N exudation from the crop roots, implying that standard methods underestimate the amount of N fixed by these crops. There is evidence in favour of both interpretations so the issue cannot be resolved at present. In either case, the amount of N available to a subsequent crop is likely to be greater than estimated.

Figure 6.2



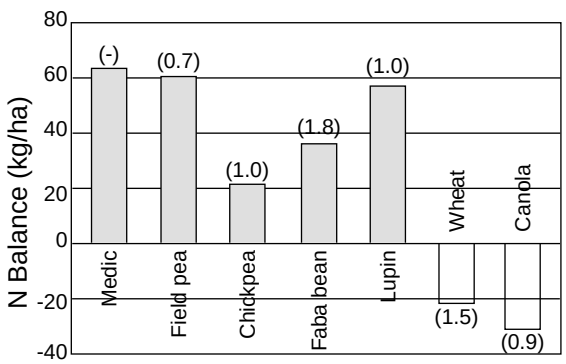
Grain yield of Kulin wheat grown in 1993 (without N fertiliser) after various pulse crops in 1992 (bars) at Pingaring. Figures in parentheses are pulse yields in 1992. Black squares show the yield of wheat in 1993 when grown after wheat with various rates of nitrogen fertiliser (top axis – unpublished data K. Siddique).

■ SOIL FERTILITY *(continued)*

Table 6.3 – Summary of measurements of the nitrogen balance of narrow-leafed lupin, field pea and chickpea crops in southern Australia (adapted from Unkovich et al. 1997)

	Total above-ground crop N (kg/ha)	% total N derived from fixation	Total N fixed (kg/ha)	N remaining after harvest (kg/ha)
Narrow-leafed lupin				
Mean	214	77	165	68
Range	53-322	29-97	30-283	-41-141
Field pea				
Mean	122	68	83	14
Range	61-227	31-95	26-183	-32-96
Chickpea				
Mean	115	60	70	8
Range	83-146	37-86	43-124	-41-56

Figure 6.3



Nitrogen balance of various crops at Goomalling in 1997. Figures in parentheses indicate seed yields (t/ha – unpublished data, A. McNeil).

Nitrogen balance

Chickpea and field pea grown in southern Australia generally leave behind less fixed N than narrow-leafed lupin. However, the net nitrogen balance varies considerably within a species depending upon other environmental factors.

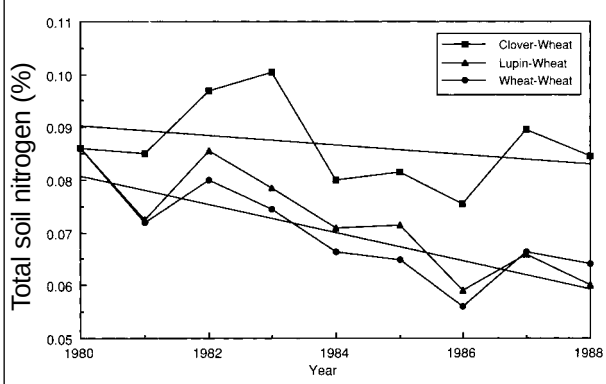
At Pingaring in 1993, wheat yields after chickpea were about the same as after field pea, but not as great as after faba bean or lentil. More than 50 kg N/ha had to be applied before the wheat yields grown after wheat were matched by wheat grown after pulses in the absence of N fertilizer (Figure 6.2).

In one trial at Goomalling in 1997, a chickpea crop yielding 0.96 t/ha produced a positive N balance of 22 kg/ha. This was equivalent to the N removed in a 1.5 t/ha wheat crop (Figure 6.3).

In Western Australia we can expect cereal yields and grain protein to be better after grain legumes than after a non-legume crop. In many, but not all cases, this will be due to improved soil N supply.

In an experiment at Badgingarra, summarised in Figure 6.4, a subterranean clover and wheat rotation maintained total soil nitrogen, but a lupin:wheat rotation and continuous wheat reduced it steadily. Thus, grain legume:cereal rotations, whilst providing significant rotational benefits, are in general not as effective as legume pasture in maintaining soil nitrogen.

Figure 6.4



Different rotations affect the rate of decline of soil nitrogen

SOIL STRUCTURE

The physical structure of surface soils as measured by such properties as soil strength, aggregate stability and porosity, improves under pasture and decreases under crop.

Changes in percentage for water stable aggregates in the Wongan Hills rotation trial (Figure 6.5), follow an almost identical pattern to that recorded for total soil nitrogen (see Figure 6.1).

The longer the length of the pasture, the greater the increase in amount of water stable aggregates. Although aggregation increased slowly under the pasture, it decreased dramatically in the first year of crop following cultivation, to establish a seedbed.

Degradation of soil structure is most significant on the fine textured soils such as salmon gum/gimlet and moort soils. These soils contain silt or fine sand in the surface and when cultivated too frequently or when too wet, slake, and form impermeable crusts.

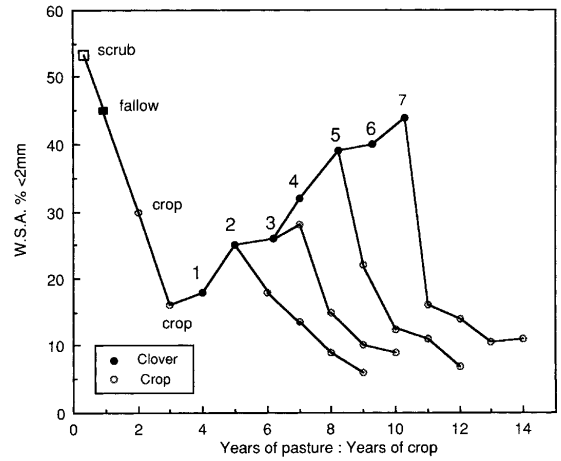
The physical degradation of some fine textured soils can mean that the soil is no longer able to absorb the incident rainfall; the soil surface becomes crusted and the soil so dense that germination and root growth are impeded. In order to maintain soil fertility and surface structural condition in an intensive cropping system, it is essential that tillage is reduced to a minimum and stubble is retained. It is also desirable to incorporate a pasture phase into the cropping program. Pasture has been shown to have a highly beneficial effect on soil structural condition by increasing aggregate stability through improved soil organic matter content.

On these (fine-textured) soils, improvement or maintenance of a porous surface structure is vital for crop production, which implies that organic matter should be accumulated in the surface. Periods of pasture are the most biologically effective way of providing organic matter.

New cropping techniques which reduce the loss of organic matter caused by tillage, are also effective in maintaining or increasing soil organic matter and structural stability in periods of cropping.

An absence of ploughing or scarifying as well as conservation of crop stubbles, will reduce the loss of organic matter by oxidation after cultivation and stubble burning. Sowing with narrow points or discs ('No-Till') will also reduce loss of organic matter by oxidation and help conserve root channels.

Figure 6.5



Pastures increase soil aggregate stability; cropping decreases aggregate stability

SOIL MOISTURE

Increases in soil organic matter should improve the moisture holding capacity of poorly textured sandplain soils.

It is possible that under pasture there may be more moisture left further down the profile because of the relatively shallow roots of the pasture legumes. This is also possible after field peas which are also relatively shallow rooted. This moisture would be available to a following cereal crop especially if there is a dry finish to the season. This is not the case with lupins which are a deep rooting plant and which remove water from deep in the profile.

■ WEEDS, DISEASES AND INSECTS

The effects of a pasture on weeds, insects and diseases appearing in the crop have been widely acknowledged, but little studied. Legume pastures are seldom monocultures but undergo changes in composition as non-legume species invade to use the increasing soil nitrogen.

Grasses, which may be important components of the pastures, are alternative hosts for the serious root disease 'take-all' (*Gaeumannomyces graminis*) and for cereal cyst nematode (*Heterodera avenae*). Some legumes host nematode diseases such as root lesion nematode (*Pratylenchus neglectus*) (see section on root disease, Chapter 10).

Cereal pests are usually more damaging after a pasture phase, as several species are able to increase in pastures and carry over into the crops. In particular, webworm, redlegged earth mite and lucerne flea are clearly favoured by pasture. This transfer into crops is aided by reduced tillage methods. Most of the other pests are just as likely to cause problems after crops.

Paddocks which have been grassy through summer and autumn are likely to contain webworm which will damage emerging crops, unless the paddock is worked conventionally or insecticide is added to the knockdown herbicide. Pasture paddocks which have not been very well grazed in spring and summer will contain large numbers of redlegged earth mite and lucerne flea eggs which will hatch in autumn/winter.

Grasses and broadleaved plants which have built up in the pasture may increase weed burdens in the following crop. One of the advantages of including a legume crop in the rotation is the opportunity it presents for improving the control of grass weeds. Broadleaved weeds are controlled more easily in the cereal crop.

LIVESTOCK PRODUCTION

The introduction of legumes into pastures has increased livestock production through the quantity and quality of the legumes themselves and through the effect of improved soil fertility on the production of other pasture plants.

A further advantage of an annual legume pasture is its potential to produce large quantities of seed. A proportion of hard seed in subterranean clover allows successful regeneration of a pasture, even when following a year of crop. With medics, the higher level of hard seed can allow regeneration after two years of crop. The seed and the surrounding burr of clovers and medics can be a valuable feed reserve for the dry summer. However, the risk of soil erosion and a reduced pasture density in the following year should not be overlooked.

Similarly, lupin stubbles give valuable summer grazing. That is, provided that care is taken to minimise the risk of lupinosis and soil erosion (by destocking before the residual seed levels fall to 50 kg/ha.

The increase in wool and meat production and inclusion of crop legumes has increased farm income and reduced income variability.

Livestock, in particular sheep, are an integral part of a sustainable farming system. With increased use of herbicides, grasses are evolving that are resistant to these chemicals. Grazing management provides an extra tool in managing herbicide resistance.

Stubble from the cereal phase of the rotation can be utilised by sheep. The grazing value of the stubbles is variable and depends on the level of grain loss during harvest and the presence of weeds in the stubble.

■ EFFECT OF LEGUMES ON CEREAL YIELD AND QUALITY

Quantitative methods are available for estimating inputs and run down of soil nitrogen for any stated rotation. These inputs can be related to yield and protein levels in following wheat crops using the SPLAT model or nitrogen calculator tables and wheels.

Legume pasture: cereal rotations

Pasture legumes, notably subterranean clover (*Trifolium subterraneum*) and annual Medicago species entered Australia in the early days of settlement, probably in fodder or on animals loaded in Mediterranean ports. It was not until 1889 that Amos Howard, a South Australian farmer, actively advocated the use of subterranean clover to improve the native pastures.

However, recognition of the value of leguminous pasture species in increasing pasture production and quality, and as a component of crop rotations, was, slow to spread.

Even as late as 1934, the then common fallow wheat: [native] pasture rotation being practised in Western Australia was criticised as incapable of either maintaining 'fertility for cropping' or of providing feed for the increasing numbers of sheep on wheatbelt farms.

The pasture year was identified as the weak link in the rotation and a modified rotation "... of continuous clover pasture for several years followed by alternate fallow and crop ..." was suggested Dunne and Shier (1934).

The key change, the lengthening of the pasture phase, allowed a prolific growth of subterranean clover that was previously suppressed in the bare fallow and crop years.

Many trials have shown the extra yield gained by including legumes (mainly subterranean clover) in the pasture phase of a ley farming system .

One such trial at Wongan Hills showed that two years of subterranean clover based pasture could lift yield by almost 1 t/ha compared to crops without pasture (see Figure 6.1). Further years of pasture increased yields only slightly. However, successive cropping decreased yields.

In another trial at Merredin (see Table 6.4), grain yields and grain protein in a number of pasture/crop rotations based on burr medic pasture (without supplementary nitrogen) were equivalent to those from continuous crops supplied with at least 80 kg/ha nitrogen. For second crops the pasture supplied the equivalent of 20 to 40 kg/ha nitrogen (Revell, 1997).

A number of these long-term pasture:cereal rotation trials in the wheatbelt have been continued for up to 20 years. These trials are of a 'fundamental' rather than of an applied nature, so not all the management practices may appear realistic. The aim is to study the long-term effects of rotation on yield and soil fertility.

The results from four trials are shown in Table 6.5. The beneficial effect of increasing the length of the pasture phase is evident, as is the decrease in wheat yield as the number of successive wheat crops is increased.

Since the 1980s there has been special emphasis on the development of new pasture species for soil types and climatic regions that were not covered adequately by traditional species such as subterranean clover and barrel

Table 6.4 – Grain yield (t/ha) and grain protein (%) for wheat crops grown either continuously with applied nitrogen or in rotation with burr medic pasture on a red-brown sandy loam at Merredin

Rate of Nitrogen (kg/ha)	1990		1991		1992		1993	
	Yield (t/ha)	Protein (%)	Yield (t/ha)	Protein (%)	Yield (t/ha)	Protein (%)	Yield (t/ha)	Protein (%)
Continuous crop								
Nil	2.17	9.2	1.02	9.1	1.04	9.5	0.57	9.7
20	2.39	10.3	1.08	9.9	1.45	9.5	0.93	9.3
40	2.46	11.5	1.07	12.2	1.75	8.9	1.50	9.3
80	2.29	13.7	1.09	15.1	2.07	10.0	1.89	10.1
1:1 pasture:crop								
Nil	2.38	12.1	1.00	16.7	2.32	9.7	1.61	9.6
2:1 pasture:crop								
Nil	2.38	12.1			2.32	10.0	2.04	10.3
2:2 pasture:crop								
1st crop – Nil			0.90	16.9			2.06	10.3
2nd crop – Nil	2.39	10.0			1.55	10.0		

PHOSPHORUS *(continued)*

Table 6.5 – Average wheat yields from four wheat:pasture rotation trials

	Yield (t/ha)			
Pasture:Crop	**Merredin**	**Chapman**	**Newdegate**	**Salmon Gums**
Continuous wheat	0.87	1.00	.040	0.89
1:1	1.06	1.66	1.16	1.31
2:1	1.09	1.88	1.46	1.42
4:1	1.21	1.93	1.65	-
3:3 1st crop	1.12	1.80	1.40	1.28
2nd crop	1.10	1.47	1.10	1.21
3rd crop	1.05	1.52	0.85	1.04

Merredin:	Sandy clay loam (salmon gum), Cyprus barrel medic (M. truncatula)
Chapman:	Red-brown loamy sand, subterranean clover cv. Northam
Newdegate:	Grey sand over gravelly clay at 20 cm, subterranean clover cv. Nungarin.
Salmon Gums:	Complex of clay loam and sandy loams, Cyprus barrel medic

medic. A particular focus was on the selection of medic species and associated rhizobia with greater tolerance to acidic soils. This work resulted in the commercialisation of cultivars of burr medic, murex medic and sphere medic. Subsequent work has identified new legume species which will complement traditional species in ley farming systems; these include yellow serradella, biserrula and balansa clover. The use of species mixtures is expected to increase the stability of the legume component of pastures, buffering the system through catastrophic events such as false breaks of season or pest outbreaks which are normally detrimental to monoculture systems (particularly with subterranean clover).

The development of phase pasture systems has also added impetus to the development of new pasture legume species. Aerial seeded species which can be harvested with cereal harvesting technology are desirable to reduce the cost of seed. New cultivars of French serradella, crimson clover and arrowleaf clover have been selected with these attributes and are now being successfully incorporated into 'phase' farming systems. Cadiz French serradella has been particularly well adopted across large areas of sandy surfaced soils with associated benefits in soil fertility and animal production. Work is now being directed towards quantifying the impact of phase pastures in terms of subsequent crop production and the control of weeds (particularly those that are herbicide resistant).

Lucerne is increasingly being seen as an integral part of sustainable cropping systems on appropriate soils (pH > 4.9 $CaCl_2$). Since the mid 1990s there has been increased research effort into the establishment and management of lucerne for wheatbelt regions with greater than 350 mm annual average rainfall. Early indications from sites at Borden and Pingrup (Latta *et al.* 1999) suggest that a lucerne rotation will use more water (60 mm over three years), have lower weed burdens, fix more nitrogen (60 kg/ha over three years) and increase grain yields relative to an annual pasture. Although the successful inclusion of lucerne in a pasture-crop rotation requires an extension of the pasture phase to a minimum of three years, the data strongly indicates that a minimum two-year, probably three-year cropping phase is sustainable. This contention is based on the measured stored soil water increasing at a rate which would allow two or three years of shallow-rooted, annual plants before recharge recommences at the rate prior to lucerne.

Lupin:cereal rotations

Proof that crop yields were improved by incorporating lupins into the rotation was provided in 1948. The data (in Table 6.6) show the marked improvements in yield and grain quality achieved by including the sandplain lupin (*Lupinus cosentinii*) in a crop rotation.

The use of grain lupins in rotation with wheat has shown that yield of wheat grown after a lupin crop is consistently greater than a wheat on wheat rotation. The two rotations have been compared throughout Australia 130 times between 1973 and 1985. The results are summarised as:

wheat-on-wheat = 1.20 t/ha
wheat-on-lupin = 1.87 t/ha
That is, a 56% average increase in wheat yield.

In 26 comparisons of the two rotations on sandy or duplex soils in Western Australia (without added nitrogen) the results are summarised as:

Wheat-on-wheat = 0.85 t/ha
Wheat-on-lupins = 1.20 t/ha

■ EFFECT OF LEGUMES ON CEREAL YIELD AND QUALITY *(continued)*

Table 6.6 – Effects of lupins on wheat grain yield and flour quality
(Data are averages for 1944 to 1947)

	Chapman		Wongan Hills	
Rotation	**Yield (kg/ha)**	**Gluten (%)**	**Yield (kg/ha)**	**Gluten (%)**
Continuous wheat	485	8.4	480	6.9
Fallow-wheat	620	6.9	950	7.4
Stubble-fallow-wheat	730	6.4	1200	7.5
Lupin-lupin-fallow-wheat	1230	8.9	1390	8.2

Table 6.7 – Details of sites of trials comparing P:W and W: W rotations

Site	pH (H2O) 0 – 10 cm	Soil
1. Merredin Research Station	6.0	Red-brown gritty clay loam
2. Narembeen	7.5	Grey-red clay loam
3. Newdegate Research Station	4.8	Grey sand over brown clay at 10-20 cm
4. Nyabing	7.3	Brown loamy sand over clay at 5-10 cm
5. Konnongorring	6.5	Red-brown clay loam
6. Salmon Gums Research Station	8.0	Brown clay loam

That is, a 41% increase in wheat yield in Western Australia.

These 26 comparisons included rates of nitrogen fertiliser. When the responses were averaged, similar rates of nitrogen were required for maximum yield in both continuous wheat and wheat-on-lupin.

Maximum yields were 1.23 t/ha for wheat-on-wheat and 1.41 t/ha for wheat-on-lupin, an advantage of 14%. The average yield advantage due to inclusion of lupins, in the absence of nitrogen fertiliser, was 350 kg/ha.

Field pea:cereal rotations.

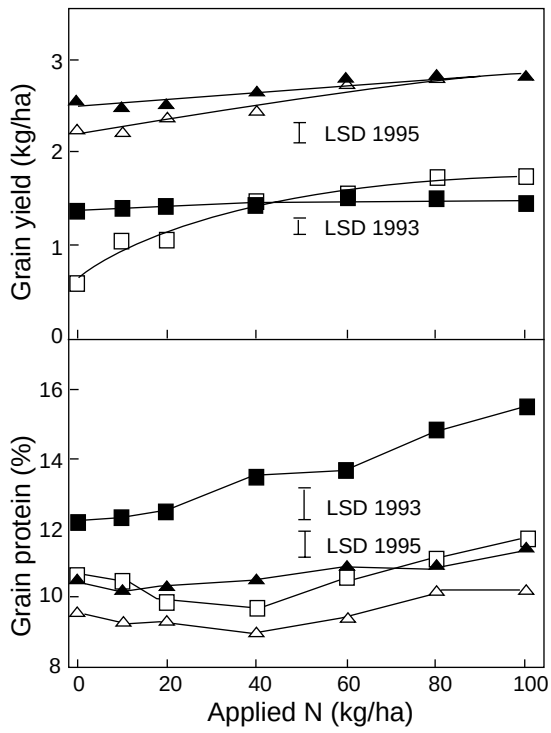
In the absence of nitrogen fertiliser, wheat following field peas (P:W) outyielded wheat following wheat (W:W) in 16 of the 17 trials (see Table 6.8). The mean yield, without added nitrogen was 0.47 t/ha higher for P:W than for W:W at 37% yield increase (Rowland et al. 1993).

In addition to a general increase in wheat yield following a field pea crop, there was an increase in wheat grain protein of almost 2% (see Table 6.8). In the trials reported, the average nitrogen content of the field pea seed would remove 39 kg N/ha for each 1 tonne of grain harvested. However, the stubble left behind had an average value of 56 kg N/ha.

Chickpea:cereal rotations

There have been few N balance measurements on chickpea in Western Australia.

Figure 6.6



Grain yield and protein response of wheat to nitrogen following wheat or chick peas at Bencubbin. Squares represent Wilgoyne wheat in 1993 and triangles, Amery wheat in 1995. Solid symbols are after chickpea in the previous year and open symbols are after wheat. LSD = least significant difference P<0.05 (unpublished data R.French).

■ EFFECT OF LEGUMES ON CEREAL YIELD AND QUALITY *(continued)*

At Bencubbin in 1993, and again in 1995, chickpea contributed about 35 kg/ha, judging by the wheat response to fertiliser N. However, no amount of fertiliser N given to wheat after wheat could raise its grain protein to that of wheat after chickpea. This indicates that non-N benefits were also involved in increasing protein levels.

On average, chickpea may not fix or leave behind as much N as narrow-leafed lupin or faba bean, but on soils or in environments where it grows better than these crops, this may not be the case. Chickpea crops that grow well but produce low grain yields are likely to have the largest N benefit.

The amounts of N left behind after a chickpea crop are usually small so it will frequently be necessary to use some N fertiliser in cereals following chickpea. This will occur after chickpea crops that had poor growth (especially if yields were moderate), in intensive continuous cropping rotations where soil organic N may already be depleted, and in years when cereals have a high yield potential.

Table 6.8. – Wheat yields (t/ha) and protein (% at 11% moisture) in a P:W or W:W rotation in years shown, at various sites

Site	Year	Field Peas/Wheat		Continuous Wheat	
		Yield (t/ha)	Grain Protein (%)	Yield (t/ha)	Grain Protein (%)
Merredin	1987	1.34	13.2	1.11	8.8
Research	1988	2.62	9.4	1.97	8.3
Station	1989	1.51	9.4	1.19	7.9
	1990	1.54	10.2	1.14	7.7
	1987	1.68	10.2	0.80	8.2
Narembeen	1988	1.51	10.3	1.53	8.5
	1989	2.01	-	1.38	-
Newdegate	1988	1.18	12.1	0.84	9.5
Research	1989	0.79	10.6	0.53	10.1
Station	1990	0.75	11.0	0.73	9.7
Nyabing	1988	1.88	11.0	1.40	8.7
	1989	1.91	9.6	1.65	8.4
Konnongorring	1988	2.95	8.0	2.30	8.0
	1989	3.18	9.0	2.18	7.4
	1990	3.15	9.5	2.12	8.0
Salmon Gums	1988	1.57	10.7	0.94	9.3
Research	1989	1.93	12.7	1.15	9.0
Station	1990	0.21	14.2	0.50	10.8
Mean		1.75	10.6	1.28	8.7

■ EFFECT OF WHEAT ON SUBSEQUENT CROP / PASTURE

Rotations are all too often discussed only in terms of the influence of the legume phase on a subsequent cereal crop. The legume benefits from the cereal as well.

For lupins grown on sandplain soils the retention of the wheat stubble is essential for control of wind erosion in the following lupin crop. The cereal stubble, with minimum disturbance seeding, helps protect developing lupin plants from sand blasting.

Also, good control of broadleaved weeds in the cereal crop can reduce their density for the following lupins.

Root diseases affecting a lupin crop are less prevalent after a cereal crop than after pasture ley. Further, the presence of cereal stubble reduces the incidence of brown leaf spot by cutting down the spread of the spores released when raindrops hit the soil.

Cereals also use up the nitrogen built up under a pasture phase. This nitrogen, if unused, would encourage the growth of grasses and other weeds in the lupin crop.

One important and well recognised effect of cereal cropping is to decrease pasture production in the years after the crop. This is invariably due to reduced plant densities resulting from in-crop weed control, and to the declining hard seed banks of the legume species.

Self-regenerating pastures based on annual legumes need to build up a reserve of seed in the soil which will persist through drought years and the cropping phase of the rotation. The legume must be capable of setting a high proportion of hard seed which will not germinate even when the soil is wet. Hardseededness and the rate of hard seed breakdown vary widely between species. For example, the medics generally have a higher proportion of hard seeds than the subterranean clovers which makes them better suited to intensive cropping systems.

Stubble residues can also lead to lower plant densities in pasture but this is normally only associated with the large quantities present in header rows.

DISADVANTAGES OF LEGUME ROTATIONS

A few disadvantages of legume rotations should be mentioned. Legumes can:

- provide too much nitrogen which produces too 'leafy' a cereal crop that is prone to 'haying off' (particularly on heavier soils in the drier wheatbelt);
- lower soil pH and increase soil acidity because of their nitrogen fixing process and accelerated nitrate leaching. Non-legumes such as capeweed present in a pasture situation appear beneficial in slowing soil acidification;
- increase water repellence, which might reduce germination of future crops and pastures and increase the risk of water erosion because of the increased organic matter produced;
- increase groundwater recharge – with risks of water logging and salinity because legumes are shallow-rooted; and
- contribute to soil structure decline in certain circumstances.

■ CANOLA IN ROTATION WITH CEREALS

Canola is an ideal break crop for cereals because it provides an excellent opportunity to reduce grass weeds and therefore minimise carry over of take-all root disease for cereals. Canola can be grown either before or after a cereal crop which makes it a flexible crop in many cropping systems.

A further possible benefit for canola is its potential for biofumigation. This is from glucosinolates in the canola plant residues that breakdown to act as a biocide. The fumigating effect of canola residue may suppress harmful soil borne organisms that attack wheat roots (for example, take all and Rhizoctonia).

Canola will maximise the profitability of any cereal based rotation throughout the Western Australia wheatbelt because of its high gross margin return.

Cereal following canola

Cereals grown on canola stubble experience few crop establishment problems. Early root diseases are usually suppressed and many growers have experienced increased early crop vigour. On paddocks which are marginal for potash (for example, deep sandplain, especially in high rainfall areas) canola residues may highlight nutrient deficiencies or imbalance where header trails are not spread evenly. It is advisable to check soil tests both between and within the header trails if there appear to be any 'wave-like patterns' in the cereal following canola.

From a nutrient management view point, cereal following canola should be treated in a similar way to cereals grown on cereal stubble. This means more nitrogen is required than if it was grown after a grain legume. Where wheat follows triazine tolerant canola in low rainfall districts with soils of high pH (pH > 6.5), triazine residues may affect the development of the wheat. Check wheat varieties for the highest tolerance to triazines if residue carryover is suspected.

Volunteer canola can be controlled by most broadleaf herbicides during the cereal phase. If large header losses have occurred it is advisable to control the volunteers on the header trails with a knockdown herbicide. Canola is generally not considered to be hardseeded.

Canola following cereal

For canola, this is the most common rotation option where a cereal crop is followed by canola. This system is useful if there is a need to reduce broadleaved weeds before growing canola or there is a risk of wind erosion

This system is a good strategy on sandplain soils that are susceptible to wind erosion and the canola is at risk from sand blasting. The cereal stubble protects the tiny canola seedlings. However, crop establishment of canola in cereal stubble requires careful management. The fine seeded canola requires good seed-soil contact. Minimum till seeding equipment is often the best way to achieve this because it allows accurate placement.

Where there are high stubble residues, they could interfere with sowing depth, chemical placement and seedling emergence. Sowing canola into high amounts of cereal stubble can also encourage insect pests that are hard to reach with chemical sprays.

Phytotoxic effects of barley stubbles can suppress germinating canola. These may be overcome by using wide-row machinery, disc or knifepoint seeders and/or removing the stubble.

When canola follows wheat higher nitrogen inputs may be needed to obtain maximum yields, but there are usually fewer problems with insects and weeds during establishment. Under this rotation canola will usually have a higher oil content when compared to canola grown on legume or pasture rotations.

ROTATIONS AND STUBBLE

All small seeded crops or pastures can have a problem if too much stubble residue is present at sowing. This can be due to cooler soil temperatures, insufficient light reaching the soil surface and the physical barrier being too thick for the young seedlings to penetrate.

Canola, mustard, clover, medic and lucerne are crops predisposed to this problem. Where there is long stubble it may be better to cut the stubble short, and chop and spread it evenly at harvest. This will encourage the stubble to break down. Alternatively not spreading the stubble at harvest but by burning or baling the header trails, (or by raking and burning or raking and baling) can reduce the problem.

■ ROTATIONS AND FARMING SYSTEMS

The integration of animals, legume pastures and crops into dryland cereal farming in the Western Australian wheatbelt has produced a stable, low-input agriculture which allows a range of cropping and animal enterprise options.

The desirable combination of crops, pastures, areas, management, type and number of livestock are determined by such things as the potential for profit, management ability, technical requirements and the resources available. However, the switching of land into or out of particular rotations generally follows changes in the relative profitabilities of the rotations. In periods of high returns for cereals, crop dominant rotations are introduced. Conversely, when animal and animal product returns are high, then pasture dominant rotations are adopted.

In the 1990s, a period of low wool prices, farming systems have become more crop-dominant. Rotations on good sandplain soils have typically involved wheat and lupins. On loamy soils some pasture areas have been displaced by canola, field peas and other crop legumes.

Often it is technically and commercially desirable to not adhere strictly to a rotation. At times, unfolding weather conditions favour increased early sowing of crops. At other times, when there has been little summer rain and the break of season is very late, then reduced sowings of crops can reduce potential losses. Besides the impact of weather, changes in relative prices of commodities can discourage the sowing of particular crops. Further, emerging problems such as herbicide tolerance in weeds or disease problems can necessitate an alteration in the rotation. In summary, land use sequences rather than fixed rotation patterns are often the norm in farming. Responding to opportunities created by weather and price conditions is often more profitable than rigid adherence to a rotation schedule.

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CHAPTER SEVEN

CROP MANAGEMENT

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■ SOWING TIME

Matching cultivar and time of sowing

The choice of sowing date and variety is the key to maximising wheat yield potential in Western Australia.

Researchers have long known that earlier sowing should mean greater yield and water use efficiency. However, early sowing was generally not adopted on-farm prior to the development of farming systems where improved herbicide technology existed, reduced tillage was practiced and high yielding, longer season cultivars were released.

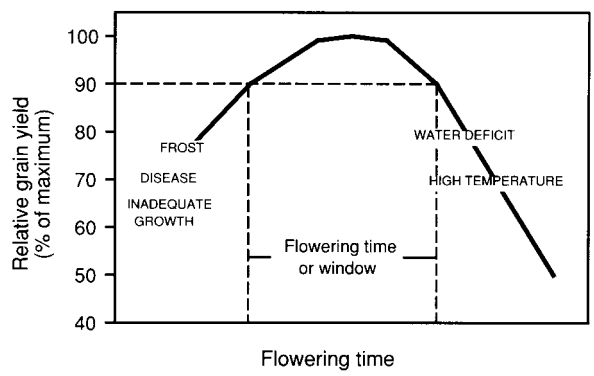
Since the late 1980s, farmers have succeeded in pushing the average sowing date of wheat from early June to mid May (2-3 weeks earlier), where seasonal conditions allow. Increased investment in sowing machinery means many growers can now sow their entire cropping program in less than two weeks from the date of opening rains. Accompanying this change, most farmers hold seed supplies of cultivars from at least two maturity groups, to allow for the likely range of timing of the cropping season. In adopting new technologies and earlier sowing for some part of their cropping program, correct matching of cultivar to sowing time has become an important decision that depends on an understanding of the idea of the 'flowering window'.

The 'flowering window'

Grain yield depends more upon flowering date than on sowing date. Research in the wheatbelt has shown that crops yield most when flowering occurs in a narrow band (or 'window') of time, usually between 10-40 days at any location.

The optimum flowering time or 'flowering window' is a balance between the risk of frost damage, disease infection or poor growth if flowering occurs too early, and the inevitable high temperatures and drought experienced if flowering occurs too late. This is illustrated in Figure 7.1.

Figure 7.1



Grain yield response to flowering time in wheat: the concept of the 'flowering window'.

It is important that crops flower in the 'window' if they are to have the best chance of achieving their maximum yield. Crops that flower before or after the 'window' yield less. The rate of reduction in yield for crops that flower after the optimum time varies for different parts of the wheatbelt, being greater in the warmer, short season environments of the northern and eastern wheatbelt, and less in the cooler, wetter and longer season environments of the South Coast (Table 7.1).

In the future, two factors may modify the situation as described in Table 7.1. Firstly, the development of longer season cultivars suitable for sowing before April 25th (the earliest advisable date with current cultivars) will extend the optimum sowing time. Secondly, there is a tendency for the higher yielding and more disease resistant cultivars to be adapted to slightly earlier sowing

Table 7.1 – Growing seasons for wheat in Western Australia. [derived from data of Anderson, Shackley, Kerr, Smith and Heinrich, 1986 – 1995]

Optimum for sowing time	Flowering Window	Days sowing to flowering		Yield penalty
		Short season cultivar	Long season cultivar	late sowing (kg/ha/day)
North-east (Mullewa to Merredin) 15/5 – 7/6	25/8 – 15/9	90	100	35
Central (Three Springs to Quairading) 25/4 – 15/5	7/9 – 27/9*	110	135	25
South (Katanning to Varley) 7/5 – 7/6	15/9 – 5/10*	115	135	25
South Coast (Welstead to Esperance) 7/5 – 7/6	3/9 – 2/10	95	140	17

* the probability of a damaging frost is at least one year in 3 for the first half of the estimated 'window' in these regions.

■ SOWING TIME *(continued)*

times than the lower yielding cultivars of similar maturity. The implications of these factors should be re-examined periodically.

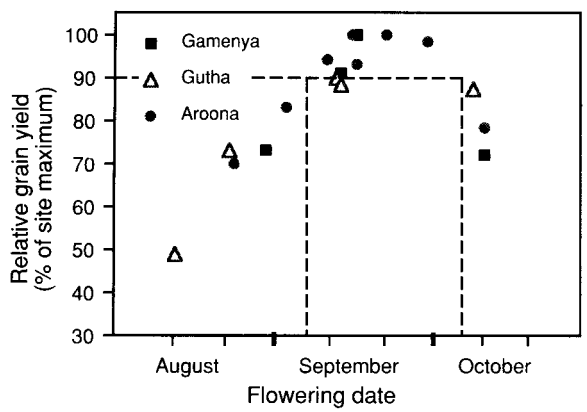
When is the flowering window 'open'?

The unpredictability of seasonal conditions such as the date of the opening rains, temperature and the incidence of frosts, means that the flowering window for any location will be open at different times from season to season.

The window can be estimated from meteorological records, but these do not account for the effects of diseases or individual cultivar adaptation and the incidence of frost damage cannot always be related to town records.

A more satisfactory method of estimating the flowering window is from sowing date experiments in the field. Flowering dates of cultivars with a wide range of maturities can then be observed and related to grain yields over a number of seasons. The best estimate will be based on some sort of average (the estimates in Table 7.1 are based on the results of over 75 experiments in the period 1986 to 1995). An example of how the flowering window was estimated from such experiments is given for one location in Figure 7.2.

Figure 7.2

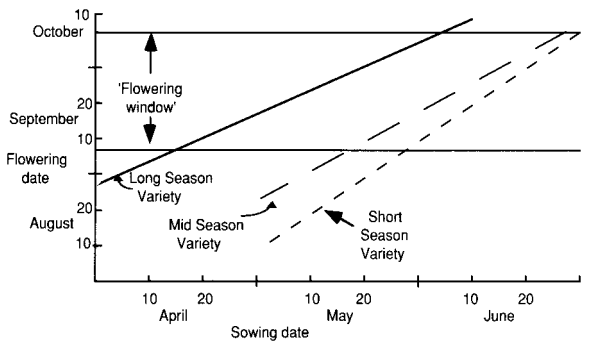


Estimated flowering window for Wongan Hills. Data are from the 1986, 1987 and 1988 seasons using the cultivars Gamenya, Gutha and Aroona.

Cultivar and sowing date

Once the flowering window is known, the next step is to ensure that cultivar and sowing date are correctly matched so that flowering will occur at the desired time. In principle, early sowing will require long season cultivars and late sowing will require short season (early flowering) cultivars. This is illustrated in Figure 7.3.

Figure 7.3



The suggested relationship between sowing date and flowering date for a long season, a mid-season and a short season cultivar at Wongan Hills.

Sowing time influences management

Sowing time influences the way the crop grows. Earlier sowings (of long season cultivars) take longer in the vegetative stage and tend to produce more leaves and tillers. Early sown crops fill their grain under cooler, wetter conditions on average and usually fill a large number of kernels to a larger size. This places a greater demand on the resources available to the crop. Later sown crops are likely to fill their grain under more stressful conditions, and factors such as nitrogen application must be considered.

Sowing time and response to nitrogen (N)

Wheat crops sown in May produce more grain on average per unit of nitrogen fertilizer applied than those sown in June. This is illustrated by the data shown in Table 7.2.

Table 7.2 – Grain yield response (t/ha) of wheat to applied N at two sowing times [data are from 15 experiments over 3 years – Anderson, Crosbie and Lambe, 1996]

Sowing time	N Applied (kg/ha)		Yield Increase
	0	40	(kg grain/kg N)
May	1.92	2.46	13.5
June	1.75	1.88	3.3

The general implication of this result is that when the cost of N fertilizer is five times the value of wheat grain (ie. it takes 5 kg of grain to pay for 1kg of N), it is more economical on average to apply N to the earlier sown crops.

Sowing time and soil type

The wide range of soils used for wheat production in Western Australia generate a wide range of water and

■ SOWING TIME *(continued)*

nutrient availability. In theory, this should lead to differences between soils in response to sowing times such that early sowing is more critical on soils with lower water holding capacity for example. In practice, there is some evidence that earlier sowing (mid-May) was more advantageous on duplex soils than on soils with a less restricted root zone (loamy sands and red-brown earths). This is illustrated in Table 7.3.

Table 7.3 – Percentage yield increases for mid-May compared to early June sowings on duplex compared to other soils [after Anderson, French and Seymour, 1992].

Experiment Series	Duplex Soils	Other Soils
1. 3 experiments, 1986-1988	16	0
2. 16 experiments, 1988-1990	37	17
Weighted Mean	34	14

In duplex soils, the disadvantage of later sowing is possibly related to the waterlogging that commonly occurs at the sand/clay interface. Less developed root systems associated with later sown crops are potentially more affected by waterlogging than those sown earlier, which would be more developed. Differences between soil types in response to early sowing imply that the better soils can be sown at the end of the sowing program with a lower risk of loss of yield.

Sowing time, diseases and pests

Denser, higher yielding crops often provide a more favourable micro-climate (higher humidity, greater supply of N and sugars) suited to the development of leaf diseases such as the septorias and rusts, as well as for insect pests such as aphids. Crops that are sown early may be more exposed to infection by Barley Yellow Dwarf Virus (BYDV) which is transmitted by autumn aphid flights, and by the leaf diseases. Infection during the early growth stages of an early sown crop, results in a far more deleterious effect on crop growth and yield than infection of later sown crops at later growth stages. In general, crops that are expected to yield over 3 t/ha are worth spraying for protection against insects and leaf diseases (see also Chapters 10 and 11).

Frost risk in early sown crops

In theory, long season cultivars sown at the appropriate time, should on average flower at the optimum time. In practice, if the weather is unusually warm and water supply is adequate, some cultivars may flower earlier when the risk of frost is still high. If this risk is judged to be unacceptable, one strategy to reduce the risk is to sow the higher parts of the landscape first, delaying the sowing of the low-lying and more frost susceptible areas until later in the program.

Sowing time and grain quality

Wheat cultivars sown at their appropriate times tend to produce appropriate grain quality as well as maximum grain yields, all other factors being equal. Sowing cultivars outside their optimum range (ie. short season cultivars sown too early or longer season cultivars sown too late), can result in small grain sievings (2mm slotted screen) above the levels acceptable for milling grades. Hectolitre weights that are below the receival standard of 74kg/hl, are also often associated with mismatching cultivar and sowing date.

In the case of short season cultivars sown too early, increased sievings and low hectolitre weights can be associated with high levels of leaf diseases, aphid infestation or frost damage. Long season cultivars sown too late have a high probability of water and heat stress during grain filling, increasing the probability of small grain sievings (<2 mm).

Grain protein levels are often increased by delayed sowing after the optimum time for grain yield. In N responsive situations this increase is about 0.033% per day or about 0.5% protein for a 15 day delay in sowing in the late May to early June period. Increases in grain protein from delayed sowing are seldom sufficient to offset the loss of grain yield over the same period which may be 25kg/ha/day or 375kg/ha.

Matching the cultivar with the sowing time not only results in the greatest grain yields but also reduces the risk of failing to meet delivery standards for test weight and small grains.

Opportunities for very early sowing

Analysis of weather records show that April sowing opportunities occur on the wheatbelt of Western Australia one year in three. Sowing as early as possible can potentially improve grain yield, with any delay in sowing leading to yield declines (from 50 kg/ha/day). April sown crops generally are exposed to warmer, more conducive temperatures for crop growth and may tolerate waterlogging to a greater extent than later sown wheat crops. However there are number of risks when sowing wheat in April, including poor crop establishment, due to prolonged dry periods after sowing and extreme temperatures and leaf diseases. No currently released variety is recommended for mid April sowing. Mid season varieties (such as Tammin and Janz) sown in April will flower too early, yield poorly and may be exposed to a high risk of frost damage (Table 7.4). At present Spear and Stiletto are the longest season varieties available, however they also flower too early. Spear displays a high level of photoperiod sensitivity and can show accelerated development if sown too early in April. These varieties can be sown with a low risk of frost damage on or after April 25. In general, no variety produces greater grain yield than Spear when sown in April (Table 7.4). Winter varieties

SOWING TIME *(continued)*

such as Osprey are also not suitable for April sowing, especially in the Eastern Wheatbelt. The cold requirement for these varieties is only partially satisfied in this environment hence development is delayed and they are subjected to end of season environmental stresses. Older varieties such as Bencubbin, with a more 'ideal' plant development pattern when sown in mid April, also have a low yield potential.

The ideal variety for April sowings needs to flower 7 to 10 days after Spear. It must display slightly longer vegetative period than Spear and have an increased vernalisation sensitivity to prevent bolting with early sowing.

Some agronomic factors to be considered if you are thinking of sowing early include:

- Minimise soil water loss through minimal tillage and stubble retention
- Higher seeding rates (70-80 kg/ha) to compensate for the possibility of seedling death from high April temperatures.
- Plant in areas with lower probability of frost
- Plant on higher water holding capacity (deeper soils)
- Sow only a small percentage of crop in April (eg. 30% max) to spread start of season and end of season risks
- Higher fertiliser applications (N) to allow for the greater biomass production associated with April sown crops compared to later sowing.
- Sow on paddocks with low weed burden as an early sowing will prevent presowing weed kill.

Table 7.4 – Flowering Dates and Grain Yields (t/ha) of selected varieties grown at Dryland Research Institute, Merredin from 1994 to 1996 during April (12-19/4) and Later Sowing (25/5 to 13/6).

	Average Flowering Date		Grain Yield (t/ha)	
Variety	**April Sowing**	**Later Sowing**	**April Sowing**	**Later Sowing**
Spear	10 August	29 September	3.15	1.81
Stiletto	8 August	29 September	1.97	1.80
Tammin	8 August	29 September	1.65	1.84
Bencubbin	24 August	29 September	1.89	1.29
Osprey	13 September	8 October	1.82	1.30
Janz	4 August	29 September	1.41	1.71
l.s.d	-	-	0.28	0.21

Source: Armstrong L, Agriculture Western Australia

■ PLANT POPULATION AND SEEDING RATE

In the past, the importance of plant population has been underestimated as other factors have been more limiting to yield. Adequate populations can be established easily with a wide range of seed rates and cereals can compensate for poor stands by tillering.

However, as other limitations to production are removed and yields are increased (particularly in high rainfall areas), plant population and row spacing may limit crop yield. It is now important to look more closely at the relationships between seed rate, plant population and grain yield.

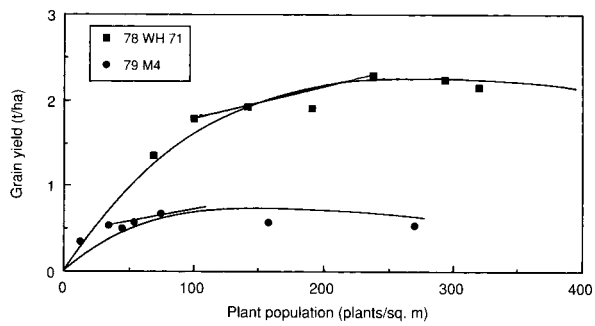
This section examines:

- Appropriate plant populations for particular environments and
- Seeding rates needed to establish the target population.

Plant population and grain yield

As the plant population increases, grain yield increases until a yield 'plateau' is reached. Yields then stay at about the same level until very high populations are reached, when yield eventually declines. This is illustrated in Figure 7.4.

Figure 7.4



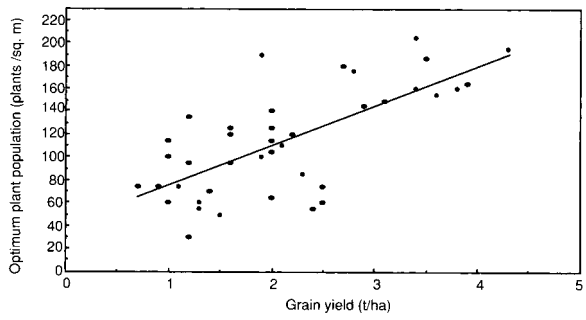
The relationship between wheat seeding rate (plant population) and grain yield. The 'optimum' seeding rate is defined as the point where an extra 1kg of seed returns 10kg of grain.

The 'optimum' plant population is that at which the cost of increasing the plant population just equals the return from increased grain yield. Because seed is cheap, the optimum plant population is very close to that which gives maximum grain yield.

Figure 7.4 illustrates the response of grain yield to plant population in two environments. An important question is whether the optimum plant population (and therefore required seeding rate) varies with site, season and variety.

Many seeding rate trials have been done by Agriculture Western Australia since 1960 and in some of these plant populations were measured. For each of these trials a relationship between grain yield and plant population was worked out mathematically and the optimum plant population determined. For this exercise, the optimum population was where the marginal return was 10 times the marginal cost.

Figure 7.5



Plant population required for optimum yield

Figure 7.5 suggests that as grain yield increases, so does the plant population required to be sure that seeding rate does not limit grain yield. For all the points in Figure 7.5, the relation between optimum plant population and grain yield was:

Optimum plant population= 40.6+ (34.6 x expected grain yield).

Thus for an anticipated yield potential of 1 t/ha, a plant population of 50/m^2 should be sufficient to ensure that plant population does not limit grain yield. At 4 t/ha, however, a plant population of about 200/m^2 would be needed to ensure that population did not limit yield. Other values are given in Table 7.5.

Table 7.5 – Plant population required to achieve yield potential

Anticipated yield potential (t/ha)	Target plant population	
	Plants/sq.m.	Plants/m row
1.0	50	9
2.0	100	18
3.0	150	27
4.0	200	36

Estimating a seeding rate

For any target plant population, the required seeding rate must be determined. Most seeding equipment is built to sow a given weight (or volume) of seed per unit area. However, the actual plant population established in the field will depend on the grain size and the percentage of grains that establish plants when sown.

Plant establishment is a result of the germination percentage of the grain and the effects of stresses in the seedbed.

■ PLANT POPULATION AND SEEDING RATE *(continued)*

Seed size

Wheat varieties have a range of seed sizes, from less than 30 mg to over 40 mg per seed. The number of seeds sown for a given weight of seed can therefore vary by up to 25%.

Seasonal effects are even greater, and for a single variety the seed size may vary from 20 to 50 mg depending mainly on the conditions during rain filling.

Percentage germination

Wheat grain generally has a germination percentage of 90 to 98% given dry harvesting weather and a lack of mechanical damage (unlike the larger pulse seeds).

Seedbed stress

Depth of sowing, disease, crusting, moisture and other stresses in the seedbed will also reduce the numbers of plants establishing. Depth of sowing is particularly important for the establishment of wheat varieties with a short coleoptile. These factors are explained in the next section – Plant establishment.

Field establishment is unlikely to be greater than 90% of seed sown and may be as low as 60% if seedbed conditions are unfavorable. 70 to 80% of seeds sown usually establish a plant.

Steps in calculating the seeding rate

- Decide on a target plant population taking into account the yield potential of the paddock, and any other factors such as weed burdens, which may indicate greater seeding rates.
- Decide what percentage of seed sown will establish plants. This combines the germination percentage with seedling establishment and will generally be in the range of 70 to 90%. If seed is suspect because of poor storage, it should be germination-tested and the establishment adjusted accordingly.
- Weigh a sample of seed and calculate the individual kernel weight. If this cannot be done, the average weights in Table 7.6 can be used, but kernel weight will vary widely depending on conditions during seed filling.

  The calculation:

  $$\text{Seed rate} = \frac{\text{plant/m}^2 \times \text{kernel weight (mg)}}{\text{expected establishment (\%)}}$$

For example, if the desired plant population is 100/m^2, the kernel weight is 40 mg and the expected establishment 75%, the required seeding rate is 53 kg/ha.

Some examples of seed rates calculated on the basis of target plant population, seed weight and establishment percentages are given in Table 7.6.

Table 7.6 – Seeding rates (kg/ha) to achieve different plant populations

Target population (plants/sq.m)*	Expected establishment (%)	Seed weights (mg/seed)**			
		28	34	40	46
55 (10)	60	26	31	37	42
	70	22	27	31	36
	80	19	23	27	32
	90	17	21	24	29
110 (20)	60	52	62	74	84
	70	44	53	63	72
	80	39	46	54	64
	90	34	42	49	56
150 (27)	60	70	85	100	115
	70	60	76	86	99
	80	52	64	75	86
	90	47	57	67	77
180 (32)	60	84	102	120	138
	70	72	87	103	113
	80	63	76	90	103
	90	56	68	80	92

* Numbers in parentheses are plants/m of 7 inch or 18cm rows.
** Typical seed weights are shown in table 7.6b.

■ PLANT POPULATION AND SEEDING RATE *(continued)*

Table 7.6b – Typical seed weights (mg)

Aroona	44	Gutha	38
Bodalllin	40	Halberd	38
Canna	33	Kulin	38
Corrigin	36	Reeves	42
Cranbrook	33	Spear	42
Eradu	38	Tincurrin	33
Gamenya	34	Wilgoyne	45

Other considerations in deciding seeding rates

The relationship between grain yield and plant population is not completely accurate, considerable variation exists. However, because of the yield plateau, plant populations above those calculated are unlikely to reduce grain yield.

It is difficult to show any consistent difference between cultivars in the yield response to plant population, although there are some exceptions. The tall cultivar, Gutha was found to require about 30% less seed to reach its maximum yield in the low rainfall zone when compared with the tall cultivar Gamenya and the semi-dwarf cultivar Aroona. Current research indicates that some of the more recently released cultivars, particularly Cascades, may have a lower 'optimum' population than Spear or Aroona. Further work is needed to clarify how the 'optimum' plant population varies with site, season and cultivar.

Current research has found that high plant populations (above 140 plants/m^2) do not necessarily lead to increases in small grains or sievings. High plant populations may lead to problems with small grains when sowing in June and with the addition of other factors such as excessive nitrogen or other nutrient deficiencies. Very high plant populations may cause small grain in very dry environments or in drought years. This is because of 'yield component compensation' (see Chapter 3) where the greater number of grain sites compete for a limited supply of 'carbohydrate'. The cultivars Tincurrin, Janz and Cunderdin are naturally small grained and may be most affected.

Greater plant populations compete more effectively with weeds, suppressing the amount of seed produced. As herbicide tolerance in weed populations increases, seeding rates may have to be increased to compensate.

The decision to re-sow

If the established population is far below the target for a given yield expectation, re-sowing could be worthwhile. The re-sown crop will have a smaller yield potential, being probably 3 to 4 weeks later and there will be some risk of it too having less than optimum establishment.

If the decision to re-sow can be made considerably sooner than 4 weeks after sowing (such as burst seed from heavy rain immediately after sowing) the decision will be easier to make.

The yield loss from later sowing and the extra cost of re-sowing have to be balanced against the yield loss from the reduced plant population at the earlier sowing. For example:

- If the crop is a long season variety sown in mid-May in the high potential yield situation, the yield expectation is 3.55 t/ha, requiring establishment of 180 plants/m^2. However, if establishment is only 50 plants/m^2 the yield potential is reduced to 2.7 t/ha. If the decision is to re-sow in mid-June, the yield potential is only 2.5 t/ha using a mid- or short season variety, and it would not pay to re-sow.
- Similarly, in the low rainfall area, if an early May sowing is chosen for a long season variety, the yield potential is 2.25 t/ha requiring 125 plants/m^2. If the establishment is reduced to 20 plants/m^2, the potential yield is reduced to 1.0 t/ha compared to an expected yield from an early June sowing of 1.5 t/ha. The value of the 0.5 t/ha difference would need to cover the re-sowing costs.

Seed source and quality

Apart from the number of plants established in the field the source of seed can affect yield.

In a set of experiments at Chapman, Wongan Hills and Newdegate in 1988 there were significant yield differences between seed sources in 9 out of 21 trials. Differences averaged about 15% between sources and were tentatively attributed to small seed size, low seed zinc content, low seed phosphorus content or some combination.

Although the experiments did not exclude other possible causes it is clear that seed for sowing should be carefully harvested from well fertilized areas, be of good size, graded and stored under cool, dry conditions -possibly in sealed, white silos.

■ PLANT ESTABLISHMENT

Plant establishment is the result of germination, management and the environment.

Germination percentage is set by the time the crop is harvested but bad storage can reduce seed viability.

At sowing, management and environment are the key issues. It is crucial for the crop to germinate, emerge and establish quickly so that yield potential is not diminished.

Depth of sowing is the main management factor involved but environmental stresses, such as waterlogging, may over-ride good management.

This section looks at depth of sowing and the effects of waterlogging on plant establishment.

Other stresses and ways to alleviate them, such as stubble retention, gypsum and direct-drilling, are discussed in Chapter 9.

Depth of sowing

Depth of sowing is particularly important because:

- Deeper seed placement delays emergence- equivalent to sowing later; and
- Seedlings emerging from greater depth are weaker and tiller poorly.

If moisture is adequate, the time from sowing to emergence is determined by the depth of sowing and the prevailing temperatures, as shown in Table 7.7. Average temperatures in the wheatbelt vary from 10 to 15 degrees Celsius during sowing and, depending on depth, seedlings will emerge in about 7 to 21 days.

Example

Estimate the time to emergence for a crop sown 5 cm deep at Wongan Hills on June 1.

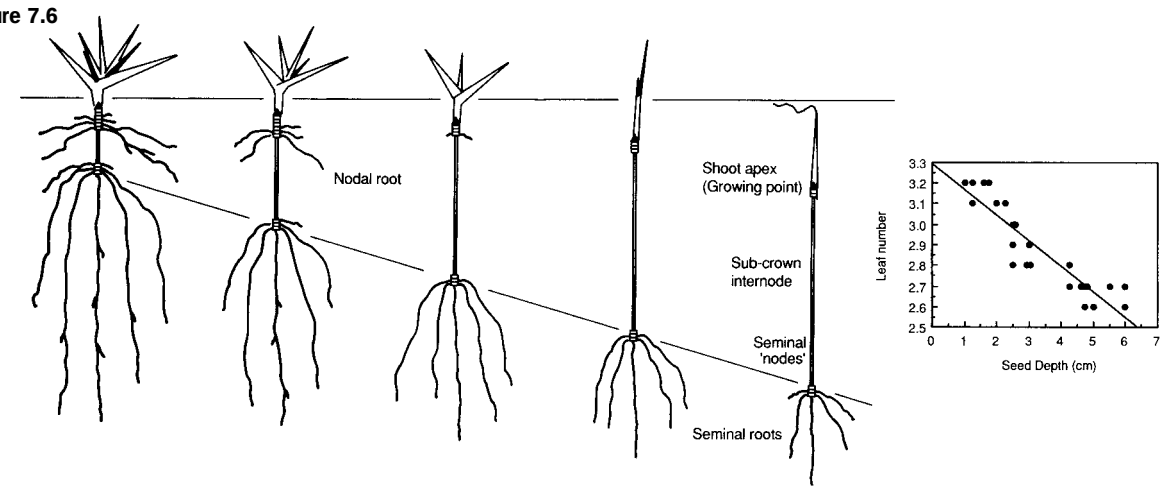
Average monthly temperatures are given in Appendix 1 for many sites in the wheatbelt. These temperatures can be used with Table 7.7 to calculate the time to emergence in moist soil.

Sown on June 1, the crop will emerge in the first half of June, average temperature over this period is best estimated by averaging the temperatures for May and June. From Appendix 1, the average temperature for May is 13.7°C and the average temperature for June is 12.1°C, which makes the average over the two months 12.9°C. Using Table 7.7, the crop would therefore be expected to emerge in about 10 days.

Table 7.7 – Effect of average temperature and depth of sowing on emergence

Temperature	Days to emergence			
	Depth of seed placement (cm)			
(˚C)	3.0	5.0	10.0	15.0
20	5.1	6.0	8.8	10.7
15	6.9	8.2	11.4	14.6
12.5	8.5	10.0	13.8	17.6
10	11.0	12.9	17.7	21.5
7.5	17.7	20.2	26.6	33.1

Figure 7.6



A representation of the effects of depth of sowing on seedling establishment. Inset: Retardation of leaf development (measured at 42 days) by increased depth of sowing

■ PLANT ESTABLISHMENT *(continued)*

As well as delaying emergence, deep sowing reduces plant vigor as is shown in Figure 7.6. After 42 days, plants sown 6 cm deep in a moist loamy sand had almost one leaf less compared with plants sown shallower. This lack of a leaf can have a pronounced effect on tiller formation and growth of the plant.

Varieties differ in their ability to recover from deep sowing. The ability depends on coleoptile length.

Coleoptile length

Semi-dwarf wheats, as well as having shorter stems, have shorter coleoptiles than the tall wheats grown in the past, so are more likely to emerge poorly if sown too deeply. Coleoptile lengths are listed in Table 7.8.

Table 7.8 – Coleoptile lengths of common wheat varieties

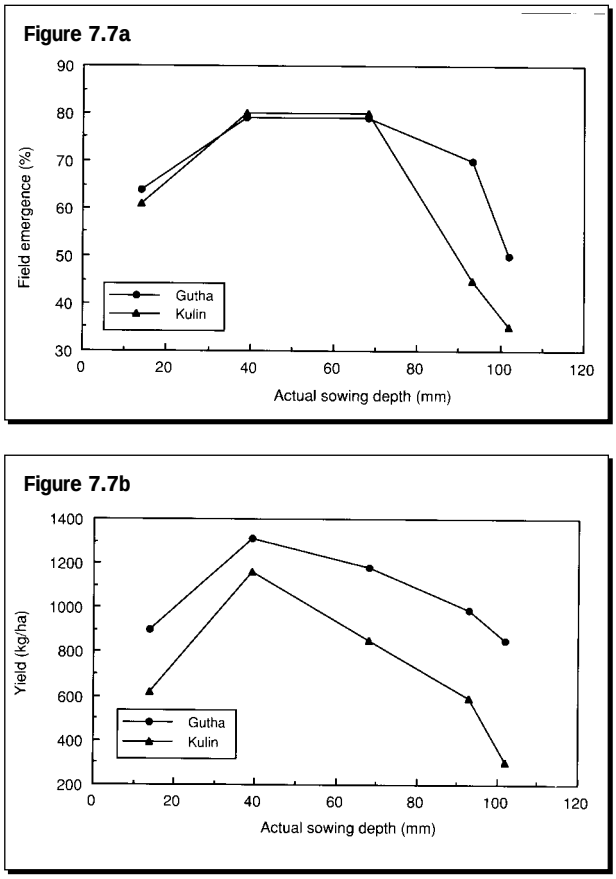
Variety	Length
Halberd	VL
Gutha	L
Spear	M
Tincurrin	M
Corrigin	M
Cadoux	L
Calingiri	M
Arrino	M
Wilgoyne	M
Kalannie	M
Kulin	S

VL is very long: greater than 90mm
L is long: 70-80mm
M is medium: 60-69mm
S is short: less than 60mm

In a trial at Merredin two varieties of different coleoptile length: a tall wheat (Gutha, 102mm), and a semi-dwarf wheat (Kulin, 64mm); were sown at five depths.

The results are shown in Figure 7.7. There was little difference in emergence up to 68mm depth but then the emergence of the shorter coleoptile wheat dropped rapidly. Kulin seed sown 100mm deep took an extra 14 days to emerge, had about 35% establishment and yielded only 25% of the plots sown at 40mm. Gutha, with the longer coleoptile, was less affected by the deeper sowing.

Sowing deeper to seek moisture in dry seasons may be justified, however varieties with a short coleoptile (including many modern cultivars) are at great risk of poor emergence.



Emergence and grain yield of a long coleotile, tall variety (Gutha) and a short coleoptile, semi-dwarf variety (Kulin) sown at five depths

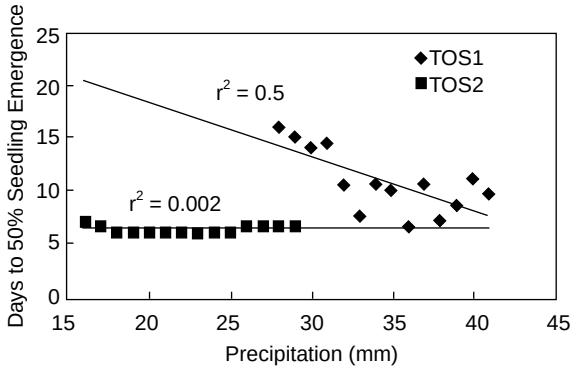
Effects of water deficit on establishment

Wheat requires an adequate amount of soil water for germination and seedling establishment. Germination will not occur until the moisture content of the grain reaches 35 – 45%. The greater the amount of soil water available to the grain, the faster the germination.

As the seedling develops it becomes more susceptible to water deficit. The amount of soil water required for good crop establishment is dependent on a number of factors including weather conditions and soil type. Fine textured soils with high clay content require more rainfall to wet up to a sufficient degree for crop emergence compared to lighter textured sandy soils. However finer textured soils once sufficiently wet will retain more soil water and will have a higher water holding capacity. Management factors such as cultivation, seeding practices, stubble retention (Collins 1998) and weed control (Fee 1997) will all determine the extent to which soil will retain water for adequate crop establishment. The greater the soil disturbance the higher the loss to soil water. Weather conditions including high temperatures and winds all can reduce the amount of soil water after a rainfall event. Poor crop emergence and establishment of early sown crops at

■ PLANT ESTABLISHMENT *(continued)*

Figure 7.8



Days to 50% seedling emergence of a Spear crop sown at two times of sowing and exposed to different water treatments after sowing at Merredin Dryland Research Institute in 1994.

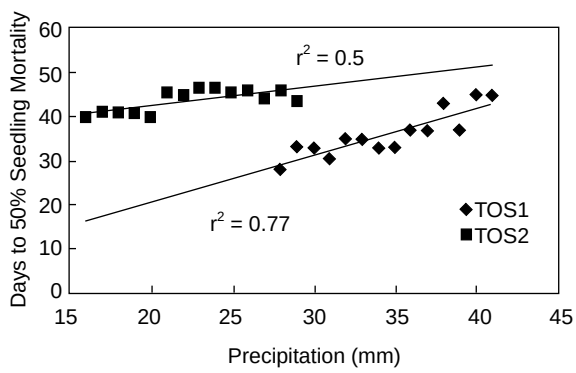
Merredin has highlighted how high temperature and high soil evaporation can result in seedling mortality (Armstrong 1999).

Field trials in Western Australia have shown that in general wheat is very tolerant to drought conditions after emergence (Heinrich 1992, Armstrong 1999). Wheat can be successfully established on as little as 15 mm of rainfall on heavy clay soil and once established seedlings will survive up to 8 weeks without follow up rain in very hot and dry conditions. It has also been found that wheat seeds which did not initially emerge after sowing, may continue to emerge if follow up rain occurs (up to 6 weeks later).

In an experiment at Merredin in 1994, Spear wheat was sown at two times of sowing and under different soil moisture conditions. Spear had reduced rates of seedling emergence and increased seedling mortality under low soil water conditions (Figure 7.8). For one sowing, seedlings which emerge on low available soil water reached 50% emergence later (after 14 days) than those emerging on better water conditions (30 or 35-40 mm, 7-11 days).

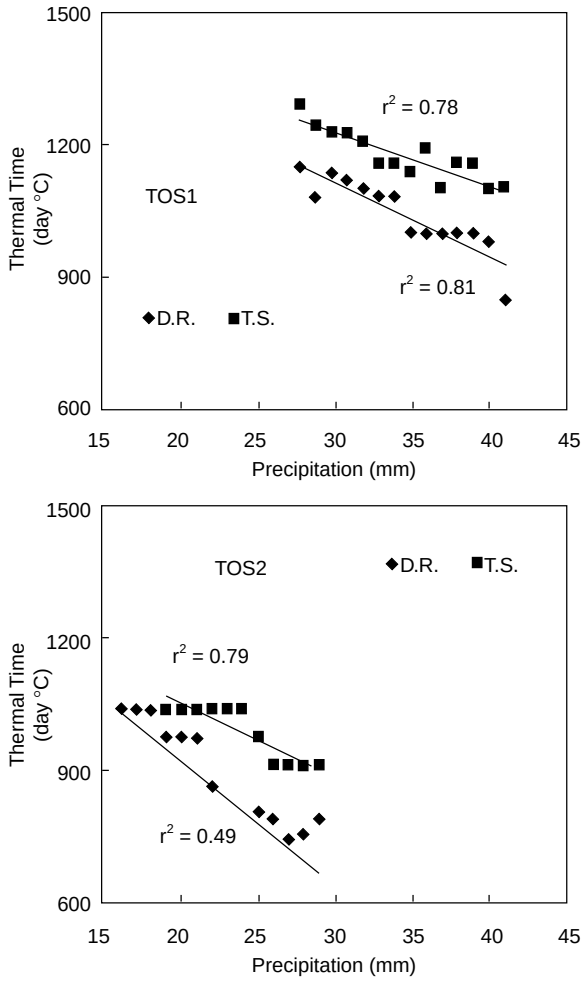
While the overall emergence of the wheat seedlings may not be effected by different soil water conditions at any one time of sowing, low soil water at seeding (eg less than 20 mm) can reduce the time to seedling death by up to 17 days. However, seedlings may survive up to 45 days suggesting that Spear wheat is very drought tolerant.

Figure 7.9



Days to 50% seedling mortality of a Spear crop sown at two times of sowing and exposed to different water treatments after sowing at Merredin Dryland Research Institute in 1994.

Figure 7.10



Timing of different phenological stages (D.R. = double ridge and T.S. = terminal spikelet) of a Spear crop sown at two times of sowing and exposed to different water treatments after sowing at Merredin Dryland Research Institute in 1994.

Differences in seedling emergence between crops sown at different times on the same amount of soil water are most likely due to other weather conditions with temperature playing a vital role in the crop's establishment (Figure 7.9). For example, crops emerging in extreme temperature conditions (TOS 1) such as 39˚C ambient and 61˚C wow is this right surface soil at 5 cm depth displayed reducing seedling emergence compared to more moderate temperatures (TOS 2).

Given the wheat crop emerges and survives the low moisture seeding conditions, if it continues to be exposed to further water stress during this critical stage of their development when leaves and tillers are emerging (up to terminal spikelet delays in growth including the time to

■ PLANT ESTABLISHMENT *(continued)*

floral initiation will occur (Figure 7.10). Ultimately, the crop may not reach full grain yield potential. Prolonged drought conditions during establishment, can dramatically effect grain production at a stage when some components of the grain yield potential is being set. It can result in phenology, rates of leaf emergence and number of mainstem leaves tiller and biomass production, and ultimately reduce grain yields by as much as 100% despite good follow up rains occurring later in the season.

Effects of waterlogging on establishment

Seed germination and establishment requires an adequate supply of oxygen in the seedbed.

In moist seedbeds, the soil gases are usually in equilibrium with the atmosphere above the soil, and oxygen concentration close to the seed is 15 to 20%.

When a soil is waterlogged, soil gases are displaced by water, oxygen availability close to the seed falls, and the seed has to depend entirely on oxygen diffusing through the water filled pores – a process 10,000 times slower in water than in air. Seeds and seedlings can therefore become oxygen deficient.

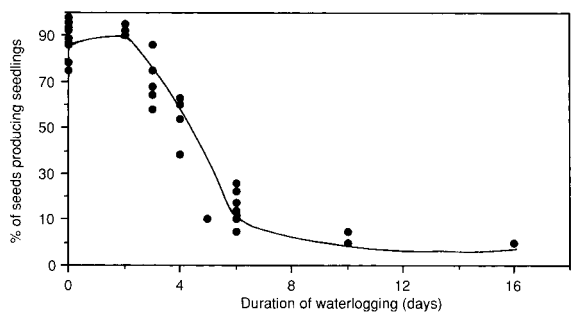
The effects of increasing the duration of waterlogging on the emergence of wheat plants is shown in Figure 7.11. After 6 days of waterlogging at about 15°C, only 20% of plants emerged. The severity will depend on temperature and soil texture.

In fine textured soils, waterlogged at above average temperatures, crop emergence will be worst.

Once seedlings have emerged, however, they are much more tolerant of excess water, as oxygen for plant metabolism can travel through the leaf tissues to reach the meristems below the ground.

The full effects of waterlogging on plant growth are described in Chapter 4.

Figure 7.11



Effect of waterlogging occurring after germination, but before emergence on wheat seedling establishment

Row spacing

The spacing between wheat plants can be varied by seed rate and by the distance between crop rows. A target plant population can therefore be achieved by several combinations of plant spacing between and within rows as shown in Table 7.9.

In theory, plants which are equidistant from all their neighbours, such as 9 cm rows and 125 plants/m^2, should do better than plants bunched together in widely spaced rows, such as 27 cm rows, 150 plants/m^2. This is because:

- Each seedling has a larger volume of soil of its own before competing with a neighbour;
- Developing crop canopies will cover the ground between rows quickly, thereby maximizing light interception and crop growth rates (see Chapter 3);
- Rapid development of ground cover will reduce the evaporation of water from the soil surface, and increase the transpiration of water through the plant (see Chapter 3); and
- Weed growth may be suppressed by the more rapid ground cover.

The size of these potential benefits will depend on the season and variety. The effects of water evaporation from soil between the rows will depend on the distribution of rainfall in the season, the amount of time the soil is wet after rainfall and the growth habit of the variety. Varieties with more prostrate growth, and/or higher numbers of tillers should cover the ground more rapidly than erect, sparsely tillering varieties.

Traditionally, cereals were sown in widely spaced rows because of the need to remove weeds between the rows

Table 7.9 – Effect of row spacing and plant population on plant density per 1 metre row.

Spacing between Rows (cm)	Target plant population(plants/m^2)			
	75	100	125	150
9	7	9	11	13
18	14	18	22	27
27	20	27	34	40
36	27	36	45	54
54	40	54	68	81

PLANT ESTABLISHMENT *(continued)*

Table 7.10 – Effect of row spacing on yields of wheat in the absence of stubble, 1982 to 1985. (Yield from the 18cm row spacing is taken as 100%).

Number of trials	Topdress	Row spacing (cm)					
		9	18	27	36	45	54
7	91	-	100	92	94	-	-
9	-	115	100	95	90	77	75
16	-	112	100	93	-	-	-
Mean response %	-9	+14	-	-7	-8	-23	-25
Kg grain/ha per cm change in row spacing	-14	+24	-	-11	-5	-23	-5

Source: Riethmuller GP, Agriculture Western Australia

mechanically. With herbicides, row spacing was reduced to the present 18 to 17cm.

It is possible to reduce the effective row spacing still further, including sowing at 9cm by using multiple tine assemblies or by broadcasting seed from a fertilizer spreader, for example.

Yields of cereals increase as the spacing between rows is decreased. Here we discuss results from work in Western Australia over the past decade, and outline the potential problems and solutions to sowing cereal crops in narrow rows.

Results in Western Australia

Trials have been conducted since 1982 in the central, eastern and northern wheatbelt, using several varieties, on a range of soil types, and in areas receiving between 210 and 390mm of rainfall in the growing season.

Row spacings from 9 to 54cm have been tested at seeding rates from 10 to 60kg seed/ha; in some trials, seed was also broadcast.

Stubble had been removed by burning.

Overall, decreasing the row spacing has increased grain yield, with an average 8% increase in yield for each 9cm decrease in row spacing from 54 to 9cm (Table 7.10).

While increasing seed rate towards the optimum generally increased yield, there was no interaction between seed rate and row spacing, that is, the yield response to reducing row spacing was the same irrespective of the seed rate used. This is not surprising since the theoretical advantages of reduced competition and faster ground cover should not rely on the number of seeds sown.

Broadcasting seed has not shown the benefit in yield that might be expected, largely because of the problems in achieving satisfactory establishment in some of the early trials.

The main effect of decreasing row spacing has been to increase the number of heads per square metre, and to a lesser extent, the kernel weight. Kernels per ear and harvest index were not affected. This suggests that reducing competition between plants has helped tiller survival and the availability of water during grain filling.

Effect of retained stubbles

Widening row spacing to make it easier to get through stubble is likely to reduce grain yield. However, one of the potential problems of reducing the row spacing has been the ability to seed through stubbles without blockages.

A key to handling stubble at seeding time, if sowing with tines, is to have the stubble in short lengths that 'flow' through the machine.

In trials, stubble was mown after harvest to leave both standing stubble and loose straw in about 20cm lengths. Trials were direct-drilled with an experimental seeder made by the Agriculture Western Australia's Machinery Unit. This machine seeded on tines on each of six bars, and had

Table 7.11 – Effect of stubble and row spacing on yield of wheat on a heavy soil (average for 1988, 89, 90, 91, 93 and 95). Yield from the 18 cm row spacing is taken as 100%.

Treatment	Row spacing (cm)			
	9	18	27	36
Stubble burnt	103	100	99	94
Stubble retained	100	100	94	93
Mean %	101	100	96	94
Grain yield (t/ha)	2.31	2.28	2.20	2.14

Source: Riethmuller GP, Agriculture Western Australa

■ PLANT ESTABLISHMENT *(continued)*

reasonable clearances between and underneath the bars to reduce blockages.

From the work so far, yield differences between burnt stubble and retained stubble treatments, and between row spacings within each treatment, have been small; interactions between row spacing and stubble have also been small as shown in Table 7.11. However, there are significant benefits for the soil and soil life by retaining stubble.

Overall, there is a trend to support the argument that narrower row spacings increase yields over a range of soil types and environments.

Adoption of narrow row spacings – problems and solutions in Western Australia

Whilst results show that reducing row spacing has the potential to increase yields in many areas, there are still problems to be overcome caused by stubble, present machinery and varieties.

Stubble handling

An appropriate stubble handling procedure from the time of harvest is necessary if crops are to be reliably established in narrow spaced rows where stubble is retained. The most important aspect may be to keep the stubble and cut straw short to ease the flow of material through the seeder if tine machines are used. Disc machines can generally handle more stubble of variable lengths, but 'hair pinning' of stubble into the seed zone can be a problem due to toxins in the stubble and a drying effect of the seed zone.

Machinery modifications

Although some older machines may be difficult to modify, many combines can be adapted to sow crops in narrower spaced rows. This requires seeding on tines on all 6 bars, and adjusting the tine pattern. The seed box may also have to be raised to allow seed to flow to all tines or fitting of an air kit.

A second problem is correct placement of fertilizer in relation to the crop rows, as high concentrations adjacent to every second or third row of plants will penalize growth of the intermediate rows – an effect which has been seen on one trial. Whether these modifications are worthwhile will depend on the yield benefit obtained.

Better plant distribution

The real purpose of thinking about narrow rows is to place plants in the ground so as to maximize the area in which each plant can develop. Thus, broadcasting seed will be almost as effective as reducing row spacing, provided the seed can be adequately covered (by harrowing, for example), and reliable establishment guaranteed.

Unfortunately, many trials in which crops have been established by broadcasting have shown poor establishment, with many seeds left close to the soil surface where they are susceptible to moisture stress. An alternative may be to use rotary harrows, or similar tools, which spread the seed in a wider band behind the tine. Using seed splitters at the base of the seeding tines will achieve the same effect. Some air seeders can do this.

Variety

At present there is little data to indicate which of the current wheat varieties, if any, are likely to respond to a reduction in row spacing. Further work is required to clarify this.

■ MANAGEMENT TO IMPROVE WHEAT QUALITY

Most quality characteristics can be modified by seasonal conditions and crop management, grain protein percentage being particularly sensitive.

However, several of the quality attributes of wheat are influenced more by cultivar than by environment or management. For example, wheat cultivars are classified as acceptable for various grades according to their grain hardness, milling and dough properties.

Growers are offered premiums for protein percentage of the grain delivered and are docked for deficient hectolitre weight or excessive small grain sievings, weather damage and admixtures. Premiums are also offered for cultivars suitable for various grades such as Noodle (ASWN) and Australian Hard, because of their qualities for specific end uses. Currently, protein percentage, hectolitre weight, sievings, weather damage and admixture are the only aspects of grain quality that directly affect the price paid on delivery.

Other quality attributes, such as flour yield and dough properties (eg. extensibility, water absorption, dough strength and development time) have a more indirect effect via the saleability of particular grades of wheat as a whole.

While crops can be managed to reduce small grains, admixtures and weather damage, the quality factor that is most sensitive to management is protein percentage in the grain.

Grain protein percentage

Grain (and flour) protein percentage (concentration) contributes more to the quality of bread products than any other factor. Protein percentage is closely linked with desirable dough properties which lead to desirable loaf properties. It can easily and quickly be measured, making routine protein testing more feasible than other more complex characteristics.

The average grain protein percentage of wheat in Western Australia has been about 10% in the 1990s. However, premiums are paid for cultivars suitable for some grades at specific protein levels (eg. Australian Premium White >10%, Australian Hard >11.5%, Australian Soft <9.5%, Noodle 9.5 to 11.5%). The proportion of wheat received into these grades has increased to over 40% of the crop since the mid-1990s.

Once a cultivar has been accepted as suitable for a particular grade the main factor that influences it's suitability for various end products is it's grain protein percentage. For pan-type breads high concentrations of good quality protein are preferred. For most biscuits and cakes grain protein needs to be less than 9.5%, while for Japanese-style white, salted noodles the ideal protein concentration is 10.5%. For Chinese- style yellow, alkaline noodles a protein concentration over 13% is preferred.

Grain protein percentage can be altered by:-

- seasonal conditions
- rotation
- N fertilizer application
- diseases
- weeds, especially grasses
- choice of soil type
- cultivar

Seasonal conditions

Water and nitrogen supply to the wheat crop are affected by the amount and timing of rainfall and by temperature. Rain during the summer months before sowing, when temperatures are higher, can assist breakdown of crop residues and release of organic nitrogen. This can improve nitrogen supply for the following crop and may increase protein percentage in the grain. Excessive rainfall during the growing season may induce waterlogging or drainage of water below the root zone of the crop. Either factor can reduce nitrogen availability, crop growth and grain protein percentage.

The weather during the grain filling period of crop growth is probably the most important factor affecting grain protein percentage. Over 80% of nitrogen in the crop is taken up before flowering and stored in stems and leaves. It is deposited in the grain in the form of protein at a rate that reaches it's maximum during the early part of grain filling. If seasonal conditions are favourable, some nitrogen is also taken from the soil after flowering and also contributes to grain protein. Carbohydrate (mainly starch) is also deposited in the grain but it's rate reaches a maximum later in the grain filling process. The eventual protein concentration of the grain is thus a result of the amount of dilution of the protein by the carbohydrate supply.

Table 7.12 – Delayed sowing increases grain protein percentage but reduces grain yield. [data are the average of 8 sites in 1987 and 1988, Anderson et al]

	May Sowing		June Sowing	
	0N	**50N***	**0N**	**50N***
Grain yield (t/ha)	2.88	3.36	2.67	3.02
Grain protein (%)	9.6	10.7	10.1	11.1

* kg/ha of N applied as ammonium nitrate at sowing

■ MANAGEMENT TO IMPROVE WHEAT QUALITY *(continued)*

Hot, dry conditions during grain filling reduce carbohydrate deposition in the grain more than protein deposition. Therefore, with a hot, dry finish to the season, grain protein concentration will be higher than where there is a cool, moist seasonal finish and more carbohydrate is deposited in the grain. This effect is clearly shown (Table 7.12) when comparing grain yield and grain protein responses from late (hot, dry finish) compared to earlier sowings (cool, wet finish). It is probably never economic to delay sowing in order to increase grain protein percentage since the increased return from protein seldom compensates for the reduction in yield.

While seasonal conditions probably have the greatest single influence on grain protein percentage, the combined effects of crop rotation, nitrogen fertilizer, diseases, insect and weed control, and choice of soil type can substantially reduce variation in grain protein percentage due to seasonal effects. For example, the data in Table 7.12 indicate that later sowing increased grain protein by about 0.5% at both nitrogen rates but the application of 50 kg/ha of nitrogen (economical for increasing grain yield in this example) increased protein by about 1% at both sowing times.

Rotation

Rotation of wheat with either pasture legumes or pulses significantly increases wheat protein percentage compared with continuous cereal cropping. Rotations with legumes also increase grain yield substantially, which is the main reason for including them in rotations. Some examples are given in Table 7.13.

Soil nitrogen, and the potential to increase grain protein percentage, is proportional to the length of the pasture phase in the rotation provided weed control is maintained. However, the most economical length of the legume pasture phase will depend on the profitability of grain production relative to animal production (chiefly wool). When profitability of the animal enterprise is high, legume pasture phases can be longer and grain protein percentages will be increased without the necessity for high rates of N fertilizer.

Growing field peas, chickpeas, faba beans or lentils on clay soils could also maintain soil nitrogen levels and produce higher grain protein percentages.

Any wheat production system which includes legumes in the rotation will probably improve nitrogen supply and provide opportunities for improved control of grass weeds and root diseases. Such systems should reduce reliance on fertilizers in the long term and arrest the decline in, or even increase, grain protein percentages.

Nevertheless, nitrogen fertilizers are often an important input for wheat production in Western Australia, yields being increased even in rotations containing legumes.

Nitrogen

Because nitrogen is an essential part of protein, its supply is an important determinant of grain protein concentration. At a given yield of 2 t/ha and 10% grain protein (close to the state average yield and protein), about 35 kg/ha of nitrogen is removed in the grain. The average application of nitrogen fertilizer to wheat crops in Western Australia is also about 35 kg/ha but typically only 50% of nitrogen applied is taken up by the crop.

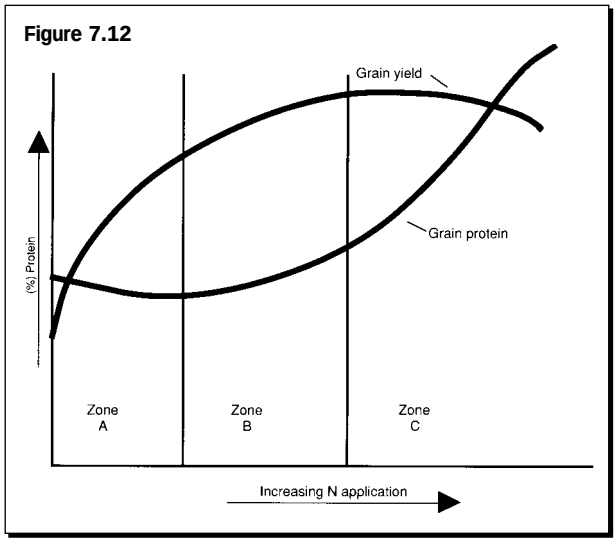
This leaves about half of the nitrogen required for the average crop that must be supplied from other sources (largely from soil organic matter).

The generalized relationship between grain yield and grain protein response to nitrogen fertilizer is shown in Figure 7.12. In zone A in the figure where there is a large yield response to added nitrogen,

Table 7.13 – Legumes included in rotations increase wheat grain yield and protein concentration. [data of I. Rowlands and M. Mason]

Rotation	Wheat Grain	
	Yield (t/ha)	Protein (%)
Medics on a loamy clay at Salmon Gums		
Continuous wheat	1.00	9.1
1 year medic: 1 year wheat	1.45	10.9
3 years medic: 1 year wheat	1.62	11.9
Peas in the eastern wheat belt		
Continuous wheat	1.34	8.7
Wheat: peas	1.86	10.8
Lupins		
Continuous wheat	1.37	9.5
Wheat: lupin	2.00	10.6

■ MANAGEMENT TO IMPROVE WHEAT QUALITY *(continued)*



The generalized relationship between nitrogen application, grain yield and grain protein percentage.

protein concentrations may fall or remain unchanged. In zone B, where the yield response is less, protein levels begin to increase. Economic rates of fertilizer will fall into zone B where yields are still responsive to nitrogen but where increases in protein level are also likely. In zone C grain protein is increased markedly but yields are not increased at all.

Grain protein concentrations (and sometimes also yield) can be increased by late applications of nitrogen, even up to the 'boot' stage of development. However, under most conditions in Western Australia there is insufficient rainfall and soil moisture to make nitrogen applied late in the season available to the crop. This practice thus has a high risk, especially in the low and medium rainfall areas.

There is an important interaction between soil type, legume rotation and response to applied nitrogen that affects the economic optimum nitrogen rate for yield and the grain protein percentage. It implies that soils with a higher clay content require less nitrogen to achieve optimum yield and achieve higher grain protein levels than sandier soils if there is a good legume rotation (see Table 7.14).

Diseases

Part of the benefit of rotation with legumes (and broadleaf crops such as canola) is to provide a disease 'break' for the wheat crop. Cereal root diseases such as take-all and crown rot that are transmitted by grass weeds can greatly reduce wheat yields (see Table 7.15).

Leaf diseases such as the septorias can also be reduced slightly by the use of a non-cereal in the rotation. Both types of diseases can devastate wheat yield in parts of Western Australia (see also Chapter 10), but grain protein percentage can be reduced as well (see Table 7.16).

Weed competition

Weeds compete with the wheat crop for water, nutrients and light. Competition for water and light will probably reduce yields but if competition for water is especially strong during grain filling it may restrict carbohydrate deposition in the grain causing pinched grain and increased grain protein percentage.

Competition for nitrogen will also reduce yields, especially when the soil supply is low. However, weed competition will also reduce grain protein levels and is especially strong in the case of competition from grass weeds (see Table 7.17).

Control of weeds in the year before cropping can increase yield and protein percentage. The effect probably comes partly from reductions in diseases and partly from increases in the soil nitrogen supply.

Table 7.14 – Soil type and legume rotation affect economic optimum N application rate and grain protein percentage.

Soil Type	Legume History	Economic Optimum* N rate*(kg/ha)	Grain protein at N opt (%)
Red clay loam	Medic or field peas	15	12.4
	Grassy pasture or cereal	36	10.5
Duplex	Sub. Clover	22	10.8
	Grassy pasture or canola	52	9.4
Sandplain	Sub. Clover	38	11.0
	Lupin	19	10.3

* the N rate required to obtain a yield response of 5kg/ha of grain for 1kg/ha of N.

■ MANAGEMENT TO IMPROVE WHEAT QUALITY *(continued)*

Table 7.15 – Relationship between grass weed control, take-all and wheat yield. [MacLeod et al., 1993]

Treatment in previous year (t/ha)	Grass dry matter in previous pasture (t/ha)	Take-all		Wheat Yield
		Incidence (%)	Severity (%)	
Nil	0.90	20	30	1.10
Spraytop	0.40	10	18	1.85
Grass selective	0.30	7	15	1.95
Broad spectrum herbicide	0.25	5	7	2.10

Table 7.16 – Weed control in the year before cropping increases wheat yield and protein percentage [data of C. Thorn]

Treatment on clover pasture in previous year	Wheat yield (t/ha)	Wheat protein (%)
Nil	1.62	12.1
Broadleaf herbicide	2.05	12.1
Grass herbicide	2.64	13.4
Both herbicides	2.91	13.8

Table 7.17 – Grass weeds reduce grain yield and protein percentage.

N applied (kg/ha)	Grain yield (t/ha)	Grain protein (%)
'Grass-free' sites (3)		
0	2.32	10.0
40	2.50	10.5
'Grassy' sites (3)		
0	1.86	8.9
40	2.26	9.3

Choice of soil type

In general, the finer textured clay soils contain more organic matter than the coarse textured sandy soils and tend to produce grain with a higher protein concentration. However, clay soils that have been heavily cropped and over-cultivated in the past can have seriously depleted organic matter and nitrogen reserves that can produce extremely low grain protein levels. Conversely, sandy soils that have been well managed with longer pasture phases, stubble retention and reduced tillage can have good organic matter content with good nitrogen reserves and produce relatively high grain protein levels.

The effect of soil type on grain protein percentage and the interaction with rotation and nitrogen requirement is illustrated in Table 7.14 as discussed earlier in this chapter. The implication is that the choice of soil type and management has an important bearing on the probability of the grain protein percentage being appropriate for various grades of wheat which receive premiums for quality.

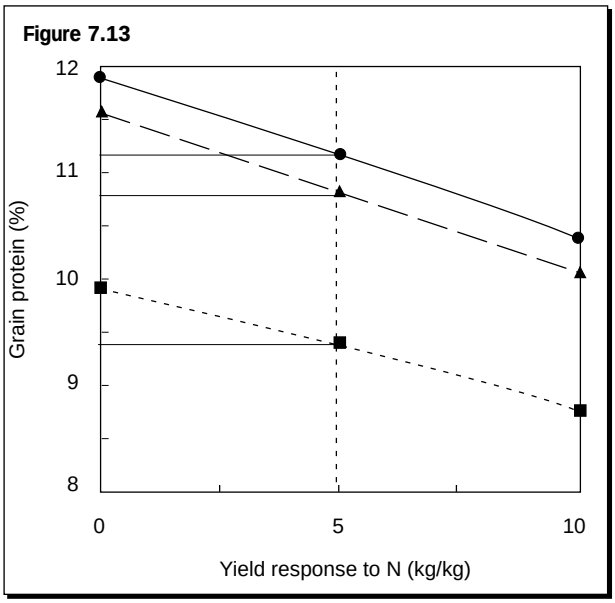
Choice of cultivar

The management factor which has the least effect on grain protein percentage is the choice of cultivar. The main differences between cultivars are those between grades or classes of wheats with differences within a grade (eg Australian Premium White) being small and variable.

The major differences between grades of wheat in Western Australia are illustrated by Figure 7.13 which contains the results from a large number of field experiments conducted from 1989 to 1993. The figure shows that at the economic optimum nitrogen rate (where 5kg of grain is produced for each 1kg of N applied, indicated by the dotted, vertical line in the figure), the grain protein percentage for cultivars that qualify for the Australian Soft grade was about 9.4%; for cultivars in the Noodle (ASWN) grade it was about 10.8%; and for cultivars in the Australian Hard grade it was about 11.2%.

Once a cultivar suitable for the target grade has been selected, the most important challenge for producers of

■ MANAGEMENT TO IMPROVE WHEAT QUALITY *(continued)*



Relationship between grain protein and yield response to applied nitrogen. ● Hard wheat, solid line, ▲ Noodle wheat, dashed line, ■ Soft wheat, bottom line.

high quality wheat is to employ management practices that will maximize the probability of achieving the required grain protein percentage.

Hectolitre (or test) weight

The weight of grain per unit volume in kg/hl is easily measured and is a good indicator of the yield of flour that can be milled from a sample of grain.

A standard of 74kg/hl has been set for all milling grades of wheat. Grain that falls below this standard is downgraded to the General Purpose or Feed grades. It is considered to be a minimum standard and wheat suitable for high quality breads or noodles are more valuable if a higher standard is achieved. For example, 78kg/hl is often more appropriate for noodle wheat and 80kg/hl is desirable for durum wheat for pasta.

As discussed earlier in this chapter the main factors reducing hectolitre weight are mismatching cultivar and sowing time, diseases, aphids and frost damage. Cultivars differ in their inherent hectolitre weight but there is rigorous selection against light weight cultivars so that modern cultivars are seldom deficient.

Small grain sievings

Excessive numbers of small grains also reduce the amount of flour that can be extracted from a sample of wheat. Delivery standards (mostly 5% by volume) are set to reflect the reduced commercial value of samples that contain excessive numbers of small grains (<2 mm slotted screen).

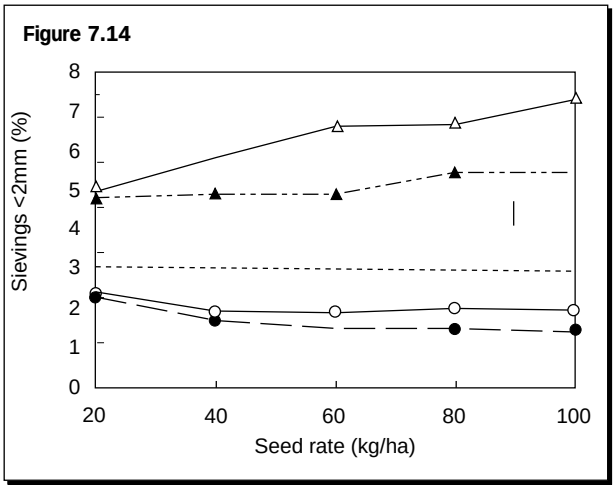
Small grains most often result when the conditions during the period when kernel or grain number is being determined (from about 20 – 30 days before and up to flowering) are more favourable than those during the grain maturation period. This can result from depleted carbohydrate supply to the grain due to diseases or insects, extremes of temperature, water supply or nutrition.

There is often more than one cause of excessive small grains in a sample of wheat. For example, sowing a cultivar after it's optimum time is less likely to produce small grains than if it is sown with a high nitrogen and seed rate as well. Increasing seed rate is as likely to increase seed size as to decrease it, depending on the paddock history. This is illustrated in Figure 7.14 where increasing the seed rate increased seed size in experiments following cereals or canola where the nitrogen supply was less but decreased it where the experiments followed a long legume pasture phase.

In soils with a marginal soil potassium test (K<60ppm), there can be an interaction between potassium and nitrogen fertilizers that dramatically affects small grain sievings. (see Table 7.18). Potassium (K) has a role in carbohydrate metabolism that means a restricted supply probably reduces deposition of starches in the grains which in turn reduces grain size (see also Chapter 5).

Deficiencies of trace elements such as copper and zinc may also play some part in the production of small grains. Such deficiencies are more likely to show up as reductions in grain yield rather than as problems with small grain.

Most modern cultivars have been selected against small grain size and so are less likely to interact with management and seasonal factors to produce excessive small grains. However, cultivars that have been selected in environments that are widely different from Western Australia may have smaller average grain size and may be more susceptible to small grain problems in this environment.



Influence of seed rate and paddock history on small grain sievings (<2 mm) in a club head wheat (Corrigin) and a standard head wheat (Reeves). △ Corrigin, pasture sites, ▲ Reeves, pasture sites, ○ Corrigin, crop sites, ● Reeves, crop sites. Vertical bar is 2 x sed. Horizontal dashed line is upper limit for sievings for acceptance into the Soft wheat grade (3% by weight, equivalent to new standards of 5% by volume).
[Anderson and Sawkins, 1997]

■ MANAGEMENT TO IMPROVE WHEAT QUALITY *(continued)*

Table 7.18 – The effect of potassium and nitrogen fertilizers on wheat yield and grain quality. [Anderson, French and Seymour, 1992]

Fertilizer Treatment (kg/ha)	Grain yield (t/ha)	Whole grains <2mm (%)	Grain protein (%)	Hectolitre weight (kg/hl)
Nil	2.27	25	11.469	
40N	1.49	35	11.7	65
60K	2.93	9	9.9	77
60K+40N	3.59	8	9.6	79

Production 'packages' for producing premium quality wheat

The 'package' approach to crop production consists of a check list of the major agronomic practices required to achieve yields that are close to the potential for the environment and season. Each component of the 'package' is based on research findings that are known to have practical application to yield improvement. Application of the 'package' can proceed by steps as resources become available and as the producer gains confidence in the idea. It is not necessary to adopt all of the 'package' at once in order to gain a yield increase in most cases. However adoption of the entire 'package' will ensure grain yields and grain quality are maximised.

The '*High Yield Package*' is comprised of 5 steps:-

- Select good cropping land
- Use a legume rotation
- Control grass weeds 1 or 2 years before the wheat crop
- Select productive cultivars and sow them at the appropriate times
- Increase nitrogen and seed rates to take advantage of the improved yield potential

Specific production 'packages' to improve the chances of producing grain suitable for premium-paying grades are modifications of the 'High Yield Package' and have also been derived from specific research projects. The 'High Protein Package' is intended for producers of wheat for the Australian Hard grade of wheat (>11.5% protein) and is also useful for potential growers of durum wheat where grain protein levels of 13% are desirable.

The "High Protein Package':-

- Select high quality clay loam soils
- Use a legume rotation (pasture or pulse)
- Control grass weeds before cropping
- Choose high quality cultivars and sow at appropriate times
- Nitrogen requirements are minimal on good clays after legumes
- Use more nitrogen fertilizer on early sown crops

For Noodle wheat, where the protein limits are between 9.5 and 11.5%, management is somewhat more difficult. Nevertheless, the success rate can be improved by the use of a more specific 'package'.

The 'Noodle Wheat Package":-

- Select sandy loams, sands or duplex soils (protein is more difficult to manage on clay soils)
- Use a good legume rotation (lupin or clover)
- Control grass weeds before cropping (they reduce yields and protein)
- Choose high quality varieties and sow at their optimum times
- Apply N up to 20kg/ha in a good legume rotation, up to 50kg/ha otherwise
- Adjust seed rate according to soil fertility, sowing time and cultivar

The goal for producers of Australian Soft grade wheat is to keep grain protein below 9.5%. This grade of wheat is produced in an area that has traditionally produced low grain protein levels but there is considerable concern about protein levels that exceed the upper limit and about dockage due to excessive small grains.

The 'Soft Wheat Package'

- Select well drained soils with good water holding capacity where possible
- Use soils with a low N status (after canola, pulses, 1 year clover pasture)
- Test soil and/or tissue for potassium
- Sow from the second week of May onwards with the appropriate cultivars
- Use seed and fertilizer rates that will optimize yield. Avoid using high seed rates if sowing late with N fertilizer.

The 'package' approach is increasingly being supplemented by techniques such as crop monitoring so that general 'packages' can be fine-tuned for individual farms and paddocks.

Management to reduce Black point

Black point is a significant quality issue, particularly for the northern and south coast regions of the Western Region. The significance of black point as a quality issue

■ MANAGEMENT TO IMPROVE WHEAT QUALITY *(continued)*

for Western Australia has largely been underestimated and as a consequence, it has not been a major priority for breeding programs to date.

Excessive black point levels have the potential to reduce flour yield and end-product quality and consequently, delivery standards are imposed to reflect the reduced value of affected grain to premium paying markets. Quality specifications for black point in premium wheat grades require that less than five percent of grain be affected.

Mechanisms for black point expression are not well understood and appear to be largely influenced by environment and crop maturity. Even though the underlying cause (biological and/or metabolic) can not be agreed upon, symptomatic expression is likely to occur only when grain is exposed to conducive conditions prior to harvest. Moist, humid conditions during crop ripening are the major contributing factors to the development of black point, so it is only a problem in some regions and seasons. This suggests on-farm management and cultivar choice can be used effectively to reduce the risk of black point by influencing the development of crop growth.

Investigation of management factors affecting black point incidence has been successful in determining appropriate strategies for implementation on farms. These factors include cultivar selection, sowing strategies and the identification of high, medium and low 'risk' areas for production. Integrated application of these management options has successfully lowered the incidence of black point, increasing grower returns directly and aiding in the placement of new cultivars within the wheatbelt of Western Australia.

Cultivar Evaluation

Evaluation of cultivar performance should balance grain yield, black point tolerance and risk of small grain screenings in estimating the likely net return. The choice of cultivars will depend on the perceived risk of each of these and other factors.

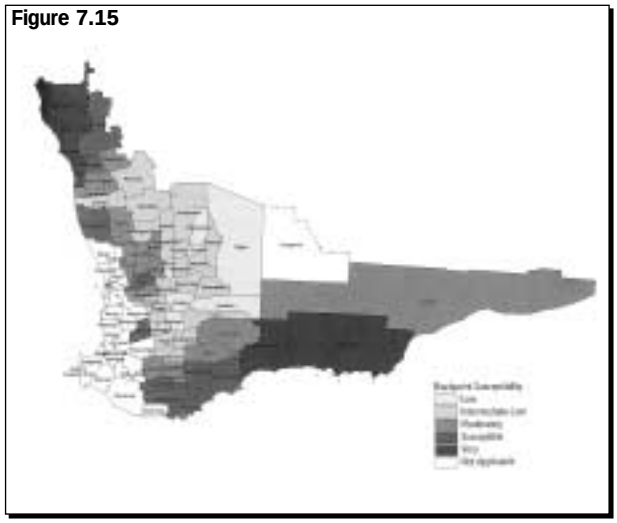
In addition to management for black point, cultivar choice is a primary factor determining risk. Evaluation of a range of new and established cultivars has indicated that there are currently no cultivars known to be completely resistant to black point, though a range of tolerances have been identified (Table 7.19).

Due to variations in cultivar susceptibility for different regions, tolerance information largely provides a comparison of cultivar risk in the development of black point, which can be utilized by growers to make more informed cultivar choices. Rankings represent the average cultivar performance expected, and estimates of the likelihood of developing black point in any season must take into account both cultivar susceptibility and area risk. In extremely wet years and in coastal areas, growers should expect poorer performance.

These rankings should be used as a guide only, as incidence and severity will vary with location. More accurate estimates of risk can be made by utilising both Table 7.19 and Figure 7.15 below.

The range of cultivar tolerance identified under different environmental and management conditions, allows a strategic seeding program to be implemented where risk is spread by seeding tolerant cultivars first, followed by cultivars which respond strongly to delayed seeding and allowing more susceptible cultivars to be sown later. By using this strategy under a range of conditions,

Figure 7.15



Guide to blackpoint risk in Western Australia.

Table 7.19 – Black Point Resistance Ratings for wheat in Western Australia

Cultivar	Resistance rating 1-9 Scale
Corrigin, Eradu, Gutha, Tammin	2 – Very susceptible
Janz	3 – Susceptible
Stretton, Blade, Arrino, Kalannie, Wilgoyne, Westonia	4 – Moderately
Schomburgk, Amery, Aroona, Carnamah, BT-Schomburgk, Cunderdin, Dagger, Gamenya, Kite, Stiletto, Nyabing, Calingiri, Datatine, Tincurrin, Cadoux	5 – Intermediate
Brookton, Spear	5/6 – Inter/moderately
Machete, Sunco, Cascades, Cranbrook, Halberd, Perenjori, Sunstate	6 – Moderately

■ MANAGEMENT TO IMPROVE WHEAT QUALITY *(continued)*

both tolerant and intolerant cultivars can be used in a program to maximize yield and gross returns for the grower, whilst achieving the best possible grain quality. However, in years conducive to black point, some proportion of grain is still likely to be affected, particularly if located in coastal regions.

Evaluation of production areas likely to be at high risk

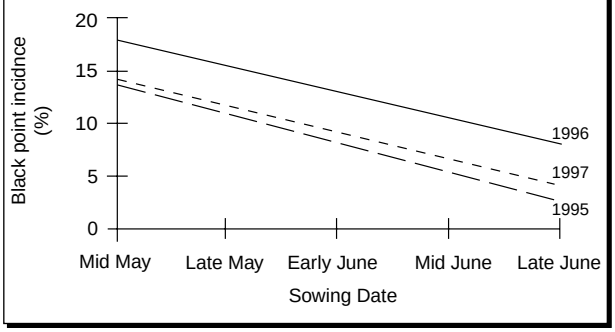
Rain during crop ripening is the major contributing factor to the development of black point, so it is only a problem in some regions and seasons. Areas which are most at risk of developing black point are indicated in Figure 7.15. These assessments will vary with season, with very wet seasons increasing the risk of black point.

Figure 7.15 indicates areas of Western Australia which are at low risk of producing black point affected grain and which are most likely to experience downgrading problems. It is also evident from this figure, that climate remains the most significant factor influencing black point. 'Areas of risk' that have been identified for the production of grain affected by black point, correlate with areas experiencing more frequent rainfall and higher humidities. These 'Areas of risks' provide a useful tool for cultivar decisions.

Time of sowing

The promotion of early sowing has the potential to increase returns through higher yields, but may also result in a loss of grain quality for areas prone to black point. Significant reductions in black point levels have been measured with later sowings, despite annual fluctuations in environmental conditions (Figure 7.16). However, in years where above average rainfall is received during grain filling and ripening, the potential for high levels of black point remains.

Figure 7.16



Linear trends for black point incidence (per cent) from 1995 to 1997.

Early sown crops are most at risk to blackpoint, particularly the more susceptible cultivars. The risk of blackpoint can be reduce by using more tolerant cultivars for seeding earlier in the seeding program. However, the development of black point is most affected by environment, and in conducive years, all grain can be affected by black point, particularly if located in coastal regions.

In general, significant yield losses were not associated with delayed sowing of up to 10 days at the majority of sites. The strength of the response and maturity type however, will largely determine those that are likely to provide an economic return by moving from a general purpose grade into a higher paying premium grade (Table 7.20). Excessively wet periods during grain development and ripening, are likely to minimize this response.

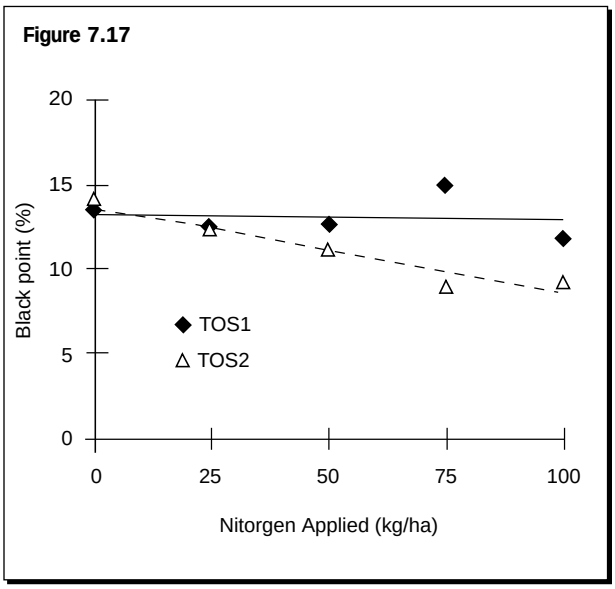
Limited trial data from the northern agricultural region, indicates black point levels decline at an average rate of 0.25% per day's delay in sowing. The response to delayed seeding on sandplain soils was greater than on the heavier clay loam soils tested.

Table 7.20 – Estimate of sowing date most likely to return maximum benefit to growers

	TOS1	TOS2
Low Rainfall Zone (< 325mm)	Brookton, Cascades, Machete, Spear, Calingiri, Perenjori, Gamenya, Westonia, Amery, Eradu, Arrino	Cadoux, Wilgoyne, Carnamah, Cunderdin
Medium Rainfall Zone (325-450mm)	Brookton, Cascades, Machete, Spear, Cunderdin Cadoux, Wilgoyne, Carnamah	Calingiri, Perenjori, Gamenya, Westonia, Amery, Eradu, Arrino,
High Rainfall Zone (> 450mm)	Brookton, Cascades, Machete, Spear, Calingiri, Perenjori, Gamenya, Cadoux, Wilgoyne, Carnamah	Westonia, Amery, Eradu, Arrino, Cunderdin

(Data is from trials located within the northern agricultural region from 1995 to 1997. Economic analysis includes grain yield and quality assessments, including protein payments based on 1998 pool returns)

MANAGEMENT TO IMPROVE WHEAT QUALITY *(continued)*



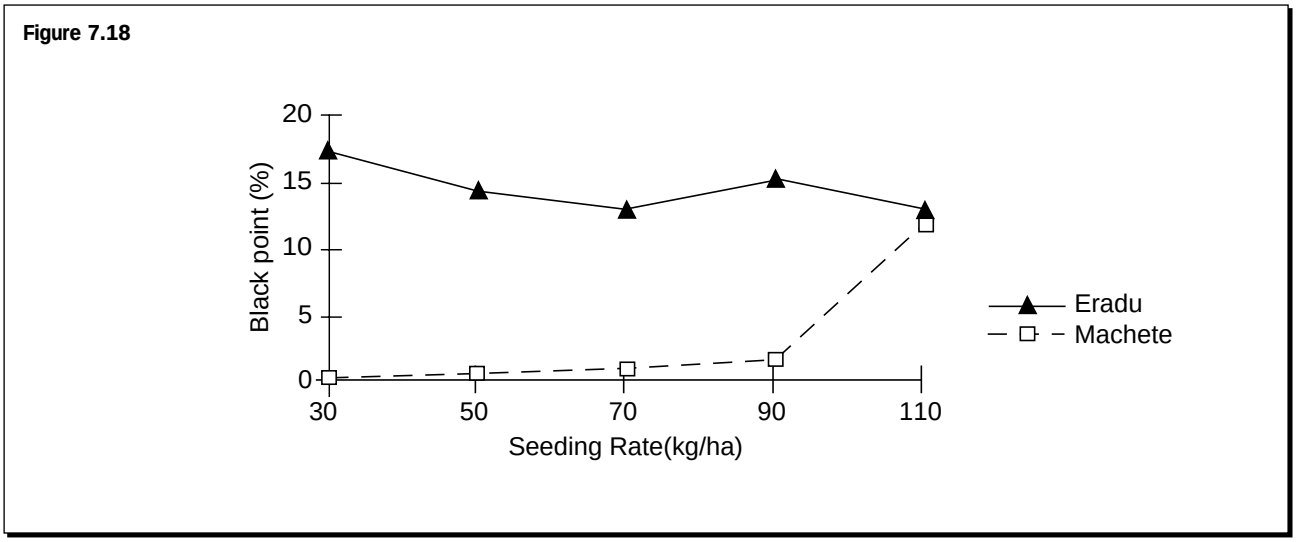
Black point response to nitrogen at different times of sowing, x sites.

This fits well with an established relationship between larger grain weight and increased levels of black point. It is rare however, that a positive economic response of black point to nitrogen will be observed.

Seeding rate

Initial seeding rate trials indicated changes in black point incidence are likely to be highly dependent on cultivar, with a positive response more likely at high seeding rates for some cultivars. The thicker canopy associated with increasing plant density may create a more favourable environment for the occurrence of blackpoint with higher relative humidity and slower drying conditions. Alternatively, the influence of seeding rate and plant density may lie in the production of less tillers and consequently larger grain size.

The influence of seeding rate on black point incidence is evident in Figure 7.18, incidence increasing between 90 kg/ha and 110 kg/ha for the cultivar Machete, whilst Eradu showed no significant response. Interestingly, a significant increase in grain weight for Machete can be associated with the increase in black point incidence, indicating the black point response may be associated with changes in grain weight for this cultivar. Response to increasing seed rates, appears to be related to the subsequent changes in grain weight, indicating a number of factors which influence grain size may be important in the management of black point.



The effect of increasing seeding rate on black point in wheat

Nitrogen

The application of nitrogen has previously been associated with changes to black point levels in wheat and past research suggests response may vary with background soil nitrogen. In the northern agricultural region of Western Australia, nitrogen application failed to significantly reduce the level of black point in three wheat cultivars on a range of soil types. Sandy soils were associated with a greater response to nitrogen, but it is unlikely that a positive economic response to nitrogen in terms of black point reduction will result.

Cultivar variations in response to soil type, time of sowing and nitrogen are evident. Figure 7.17 indicates the response to nitrogen is more evident at later sowings and with higher nitrogen rates, where grain is generally smaller.

Climate

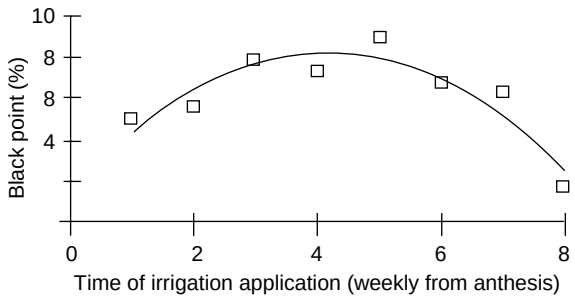
Rain during crop filling and ripening is the major contributing factor to the development of black point, so that it is only a problem in some regions and seasons. However there are other contributing factors such as crop maturity. Through multiple regression, 84% of variation in

■ MANAGEMENT TO IMPROVE WHEAT QUALITY *(continued)*

black point incidence was found to be attributable to cultivar, the number of rain days, average daily temperature and flowering date. Currently, the most susceptible growth stage for the development of black point has been identified as approximately four weeks after flowering (Figure 7.19), though grain is susceptible throughout most of its grain filling and ripening cycle.

The influence of drying winds is also likely to be significant. Late rains are less likely to increase black point damage significantly as grain susceptibility appears to decrease at lower grain moisture content.

Figure 7.19



Average black point levels for Eradu wheat irrigated from anthesis for 6 weeks (total irrigation applied 16mm) in 1996 and 1997

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■ MANAGING FROST RISK TO MAXIMISE CEREAL YIELDS IN WESTERN AUSTRALIA

Introduction

Spring radiation frosts have been an irregular, but spectacular cause of crop loss in Western Australia, with many growers suffering some loss of income from frost damage every year in susceptible areas. Advances in cropping technology during the 1980s and 1990's have increased the industry's exposure to spring frosts. These changes are:

i) greater emphasis on continuous cropping resulting from good wheat prices and low wool value,
ii) release and widespread adoption of early flowering wheat varieties,
iii) emphasis on early sowing of cereals to maximise yield potential, and
iv) improved technical ability to sow early (i.e direct drilling, herbicides and larger machinery).

Severe and widespread frost damage was experienced over large areas of the Great Southern and Eastern wheatbelt in 1998. Other serious and widespread frost events also occurred in 1981 and 1985 and 1994 with smaller areas of damage in 1977, 1979, 1980, 1982, 1984 and 1988. The severe frosts in September 1998 reduced the state's wheat yield by an estimated 1 million tonnes. It is estimated that in the last decade frost has cost Western Australia's wheat industry an average of about $1.2 million per year in actual damage to crops. As a result of these damaging frosts, some farmers in susceptible districts are reluctant to sow crops early, even though yield advantages from early sowing are achievable. Consideration must be given to frost risk management over the whole property with special emphasis on managing areas that are consistently frost affected.

Climatology of Frost

Radiation Frost

Radiation frosts usually occur on clear and calm nights when heat from the crop surface flows (radiates) back to the sky at night. The synoptic situation that most commonly leads to these conditions is shown in Figure 1.7 Chapter 1.

The synoptic situation shows a cold front passing over the South West of Western Australia bringing cold and wet conditions with very little heat input from the sun during the cold and cloudy day. A high pressure system follows, allowing the influx of cold S-SW airstreams and rapidly clearing conditions. Very low daytime temperatures coupled with a clear and calm night results in very high heat flow back to the sky and ultimately frost.

Landscape Effects

As warm air rises, it is replaced by cooler air. This cool air will flow downslope. This is known as "Katabatic" air flow (or "Katabatic wind,") and is the reason why the severity of frost damage from radiation frost is usually more in low lying areas. Cold air can collect against mid-slope barriers (trees and fences) which can also lead to localised frosts in these areas.

Standard Temperature Measurement

The Bureau of Meteorology standard for temperature measurement is the temperature measured inside a screen (white louvered box or shelter) at 1.3 metres above the ground. This is the **"screen air temperature"** and is what you will see quoted in the media. Standardisation of temperature measurement is extremely important as it allows accurate comparisons to be made between locations.

It is very difficult to define a relationship between the screen air temperature and temperature within the crop, as many microclimatic factors are involved. An approximate rule of thumb is that **crop temperature will usually be 2-3˚C below the screen air temperature.** With this rule of thumb in mind, a frost on the ground is defined as when the **screen air temperature** has reached +2.2˚C or below.

The temperatures referred to in the remainder of this chapter are crop temperatures, unless stated otherwise.

Crop development and frost damage

Frost damage results from a complicated interaction between the environment and the plant. Soil type, soil moisture content, cloud cover, daytime temperature, wind speed, humidity, position in landscape, crop species, crop nutrition, crop density and crop moisture status all influence the occurrence of frost and the resulting level of crop injury. Of particular importance is how the crop's tolerance to frost changes with its stage of development (Table 7.12).

Pre Stem Elongation

During seedling growth and tillering the apical meristem (growing point) of cereals remains below the soil surface, insulating it from freezing temperatures. Provided the soil remains unfrozen, crop temperatures above -8˚C rarely kill the meristem of the plant, and although the leaves may be severely blighted, the apical meristem will continue to produce new leaves and tillers. Leaves become frozen at crop temperatures below about -2˚C and appear water soaked and wilted. Several days after the damage has occurred they dry out and become a brown, hay colour. Damage at this stage usually goes unnoticed and has minimal impact on crop yield.

Stem Elongation

During stem elongation and booting the meristem grows away from the protection of the soil, towards the top of the canopy. Crop temperatures need to fall to -4˚C or below to freeze stems or heads during these stages of development. Partial freezing of the nodes of the stem and the developing ear can distort subsequent growth of these tissues which is easily mistaken for damage caused by

■ MANAGING FROST RISK TO MAXIMISE CEREAL YIELDS IN WESTERN AUSTRALIA *(continued)*

Table 7.12 – The dates after which the risk of a damaging frost is equal to 1 in 10, 5 and 3.3 years at various locations in the W.A.estern Australian wheatbelt. Also indicated are the estimated critical temperatures for each MET station.

Frequency	Critical Temp. (˚C)	Frost Risk		
		10 % 1:10 years	20 % 1:5 years	30 % 1:3.3 years
Location				
Bridgetown	1.0	Nov 3	Oct 29	Oct 23
Kojonup	1.5	Nov 1	Oct 23	Oct 17
Wagin	1.5	Nov 1	Oct 28	Oct 16
Salmon Gums	0.5	Oct 27	Oct 21	Oct 13
Pingelly	2.0	Oct 25	Oct 19	Oct 11
Brookton	1.0	Oct 27	Oct 17	Oct 10
Katanning	2.0	Oct 24	Oct 17	Oct 9
Corrigin	1.5	Oct 28	Oct 13	Oct 7
Beverley	0.5	Oct 25	Oct 16	Oct 6
Goomalling	1.5	Oct 21	Oct 13	Oct 5
Kondinin	-0.5	Oct 17	Oct 8	Oct 1
York	1.5	Oct 17	Oct 7	Sep 30
Collie	1.0	Oct 13	Oct 4	Sep 29
Lake Grace	2.0	Oct 13	Oct 5	Sep 28
Mount Barker	3.0	Oct 13	Oct 5	Sep 28
Narrogin	2.0	Oct 12	Oct 4	Sep 28
Wongan	2.0	Oct 17	Oct 6	Sep 28
Northam	2.0	Oct 8	Sep 30	Sep 24
Hyden	0.0	Sep 28	Sep 22	Sep 19
Cunderdin	2.5	Sep 27	Sep 23	Sep 17
Kellerberrin	1.5	Sep 25	Sep 20	Sep 16
Narembeen	1.0	Sep 28	Sep 21	Sep 16
Bencubbin	1.0	Oct 9	Sep 25	Sep 16
Merredin	0.5	Sep 30	Sep 21	Sep 15
Southern Cross	0.0	Oct 3	Sep 11	Aug 31
Wandering(Avg)	0.0	Oct 29	Oct 21	Oct 15
Wand.(Ridge)	-2.0	Sep 22	Sep 15	Sep 2
Wand.(Val.Flr)	2.0	Nov 22	Nov 16	Nov 11

There are considerable differences in the risks between regions, however at most locations, the risks were small by late October (Table 1). At Bridgetown there is a 30% risk (i.e. 1 year in 3.3) of a damaging frost occurring after October 23 whereas at Merredin, the 30% risk occurs after September 15. The region of greatest frost risk is approximately between York, Corrigin and Katanning (Fig. 7.13).

■ MANAGING FROST RISK TO MAXIMISE CEREAL YIELDS IN WESTERN AUSTRALIA *(continued)*

hormonal herbicides, nutrient deficiency, disease or moisture stress. Blistering and cracking of the stem as a result of freezing may also restrict the translocation of photosynthates to the developing ear.

Post Ear Emergence

Wheat plants are most susceptible to frost injury after ear emergence and at flowering when the ear and sensitive reproductive structures are directly exposed to the surrounding air. Frost damage can occur at any time from ear emergence to the hard dough stage. In the Western Australian wheatbelt these stages of development often coincide with damaging temperatures in September and October, usually on clear, still nights after a cold front passed across the south-west of the state. When a damaging frost occurs within a week after ear emergence, stems, florets within ears or whole ears are often visibly blighted. Alternatively, only the reproductive parts may be damaged, and although they may appear unaffected, they produce no grain. Damage after flowering usually results in pinched or destroyed grain, either from stem damage or direct damage to the developing grain. Similar symptoms also occur with copper deficiency, root disease or moisture stress, however unlike frost damage, these symptoms damage all ears and usually follow soil type.

Assessing frost damage

If frost damagee is suspected, timely identification of symptoms and estimates of the degree of damage will help decide whether the crop should be left to harvest, or other measures should be implemented to salvage the crop. Possible salvage measures include; cutting for hay, cultivating the crop into the soil, grazing or spraying. Each of these options has its merits and drawbacks and will depend very much on the individual situation. (see “Dealing with Frost” in the Further reading section).

Important points to consider when assessing frost damage:

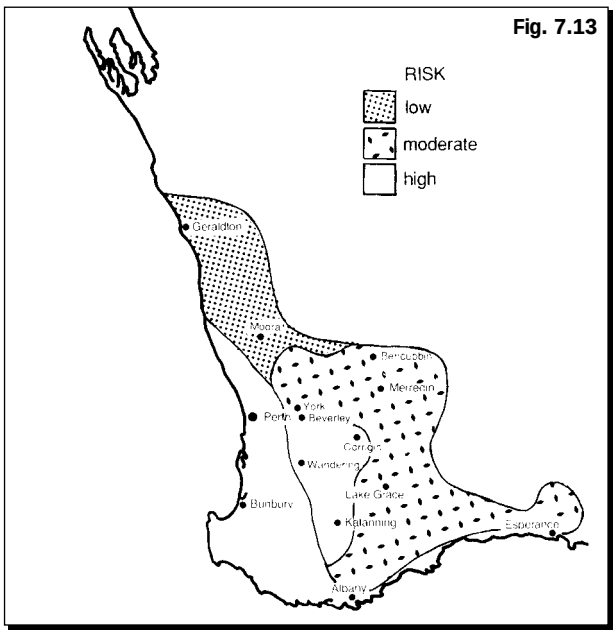
- Damage is likely to be sporadic within a paddock and the overall loss will be very difficult to assess.
- Damage can occur at any time between booting and hard dough therefore crops should be inspected between booting and late grain fill stages when screen air temperature falls below 2˚C at the nearest Bureau of Meteorology (MET) station.
- Check low lying and natural drainage areas first, light coloured soil types, and areas with a history of frost damage.
- Peel back leaves and open the florets to check for stem and head damage (See Plates/Fig/Frost ID Guide****.)
- Tag five to ten ears with ribbon or plastic strips. Note the stage of growth and return every 2 days or so to check if grain growth has ceased or not.
- Some compensatory growth often occurs in the unaffected grains and often higher grain yields are achieved than first estimated.

Analysis of frost risk

In order to manage frost risks to maximise cereal yields, we need to have some knowledge of what the risks are in Western Australia. Frost risks vary between farms and districts or regions.

Regional Frost Risks

The difficulty in analysing frost risks from Bureau of Meteorology data is that there is a variable difference in the temperatures recorded by MET stations and the temperatures experienced by crops in paddocks as discussed earlier. The low spatial density of official MET stations is also a factor. In order to account for this variation, an attempt was made to calibrate the temperature readings recorded at MET stations to observed frost damage to cereal crops in the surrounding districts (Loss & Perry, 1988). Dates when frost caused damage to cereal crops were obtained from farming communities and for each report the minimum temperature recorded at the nearest MET station was examined and the average critical temperature was calculated for each MET station. The risk of temperatures less than the average critical temperature (i.e. a potential damaging frost) was determined for various times of the year using historical data from the Bureau of Meteorology. These risks are presented in Table 7.12 for each station, in order of risk.



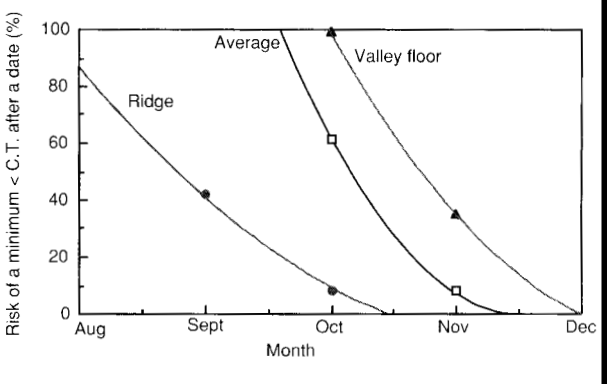
Risk of frost injury across the wheatbelt.

■ MANAGING FROST RISK TO MAXIMISE CEREAL YIELDS IN WESTERN AUSTRALIA *(continued)*

Frost Risks Within Regions

Frost risks can vary as much within regions as between regions, largely due to the effect of landscape and crop factors. During radiation frosts, dense cold air tends to move in the natural drainage lines to the lowest points the landscape. The regional analysis of frost risk can also be used to gauge the effect of position in landscape on the risk of damaging temperatures. At Wandering, temperature differences of 4.0˚C have been recorded between a ridge and valley floor, about 400m apart. If we consider the critical temperature for the ridge to be 2.0˚C and -2.0˚C for the valley, the risks are changed quite dramatically (Table 7.12). Figure 7.14 illustrates how at Wandering, the risks can change between the average position in the landscape and a valley floor. In contrast, the risks at a ridge much smaller, however crop factors and soil type can a have dramatic impact on risk in these areas.

Fig. 7.14



How position in the landscape influences air temperature.

Limitations of analyses

The calculated frost risks have some limitations. It appears the calibration method was more accurate for some stations than for others. One may have expected that the risks at Narrogin to be more similar to those at Pingelly and Corrigin, which is not the case with the estimated frost risks (Table 7.12). Also the risks at Salmon Gums and Wongan Hills appear to have been over estimated. All MET stations analysed had between 29 and 16 years of temperature data. In cases where the temperature records were short and only one day in a month was recorded less than the critical temperature for the station, an inaccurate reading could cause an error of between 5 and 10 %. Also the analysis gives an estimate of the risk of a damaging frost but the extent of the damage caused by the frost is not defined. The level of damage can only be assumed to be at least that detected by most farmers, since the calibration method was based on farmer reports of frost damage.

Managing frost risk

There are many methods employed by intensive crop industry to minimize frost damage, however none are economical for broad acre crops., In individual years on individual farms frost damage can have devastating effects on production and income. The level of risk a farmer wishes to take is a personal decision and he or she may feel more comfortable accepting a low frost risk, knowing that the return will be more stable even though it may not be maximised in the long term.

Time of Flowering

At present, the main method of reducing the amount of frost damage in wheat crops is to manipulate the crop's time of sowing and development so that flowering is delayed to a time of low frost risk. Studies have shown that the total elimination of frost damage by delaying sowing and hence flowering, will not result in maximum long term yields because of the irregular incidence of frosts and more regular incidence of dry conditions during grain fill. For example, a farmer may produce higher long term yields on most parts of the farm by sowing early, even though 1 year in 10, frost will destroy the whole crop.

Many studies in Southern Australia have demonstrated how yields decline at approximately 1% for each day delay in flowering, past an optimum date and this can be attributed to less efficient water use during the vegetative stages of growth and increased high temperature and moisture stress during grain filling (Doyle and Marcellos, 1974; Fischer, 1979; Kohn and Storrier, 1970, Perry et al., 1989).

If we consider a wheat crop sown at the average position in the landscape at Corrigin which emerges from the boot on October 7, the risk of a damaging frost occurring after this date is 30% or 1 in 3.3 years. If the crop was sown later and emerges from the boot on October 13, then the frost risk is reduced by 10%. If we assume a damaging frost reduces the yield of the crop by 50%, then the crop sown earlier will yield 5% less than the later sown crop because of greater frost damage. However the later flowering crop is likely to incur a yield penalty of 6% (i.e. 1% per day delayed flowering). The results of this type of reasoning give similar results at other sites.

Row Spacing and plant density

Current frost research work in Western Australia indicates that adopting wide row spacings in frost susceptible areas results in warmer crop canopy temperatures, reduce the level of frost damage occurring in the crop. Heat energy flow is the mechanism believed to be involved. The work is continuing on a range of soil types and tillage systems.

■ MANAGING FROST RISK TO MAXIMISE CEREAL YIELDS IN WESTERN AUSTRALIA *(continued)*

Management of paddocks according to risk and position in the landscape

The analysis of frost risk indicates the importance of the effect of landscape on the risk of frost damage. The high risk regions of the Western Australian wheatbelt also have undulating landscapes which magnify the risks. Farmers in these regions usually have some knowledge of the frost risks of their paddocks and they sometimes sow ridges and other low risk sites before progressing to paddocks lower in the landscape. The use of satellites and GPS technology is being investigated in the current frost project, to aid in accurate identification of susceptible sites on individual farms.

Choice of Crop and Variety

It is generally accepted that oats are much more tolerant of frost damage than barley, and that barley is slightly more tolerant than wheat. Research in NSW and Queensland suggests that the critical crop temperature for severe yield loss in wheat is about -3.8˚C, and for barley, -4.5˚C. Sowing oats in high risk parts of the landscape is one method adopted to minimize frost damage. Wheat breeders in N.S.W. and Qld have been breeding for frost tolerance for more than 25 years, however the difficulties of the selection techniques have caused slow progress. Screening programs are continuing at present. There are differences in the patterns of grain growth of Australian wheats (Loss et al. 1989). It appears that late flowering is related to shorter more rapid grain growth which could be exploited to delay flowering without a reduction in yield.

Frosted crop salvage options

If frost damage is suspected, timely identification of symptoms and estimates of the degree of damage will help decide whether the crop should be left to harvest, or other measures should be implemented to salvage the crop. Any crop material that is not harvested will have to be removed prior to seeding the following season.

Harvesting the crop, although a heartbreaking task in many cases, is still considered a good option, as it deals with the crop in the usual way, utilising the machinery and skills already available. Any remaining grain from compensatory growth will also be collected.

The approach taken by an individual will depend on the individual's situation including; skill level and attitude to risk, availability of machinery, availability of markets, cost (monetary and time/labour) and the relative advantages and disadvantages of the options available at the time.

Cutting Crops for Hay

Oversupply of hay is usually a problem when large areas of crops or districts are affected by frost. Cutting crops for hay is therefore only an option if the hay can be used on farm or a market contract is available.

Other important factors to consider are:

Assess paddocks carefully for the level of damage and likelihood of recovery. Only a proportion of the paddock may be so severely affected to warrant cutting it down.

Cutting a crop for hay should be done as soon as possible to prevent decrease in feed quality, but proper assessments should be carried out to avoid rash decision being made.

Is the appropriate machinery and labour available?

Silage

Advantages

Frosted crops may be suitable for the production of silage if they are still relatively green with plenty of leaf material. If so, the resultant feed may have a greater nutritive value than if the crop were cut for hay. Producing silage will ensure that stubble is managed in readiness for next season. If weeds have not set seed this option helps reduce the weed burden in the paddock. This option is especially viable where the grower is equipped to produce silage.

Disadvantages

Cereals, especially wheat, produce poor quality silage when compared to other crops. If the skills and machinery required are not readily available then the production of silage becomes expensive. Another point to consider is the harvesting of nutrients associated with silage production when compared to other options such as green manuring and some cutting/grazing options.

Cutting operations

Advantages

Swathing/cutting can preserve some of the nutritive value of the crop without the expense associated with applying desiccant herbicides. Cutting retains nutrients either through fodder conservation or recycling of plant material. This option also has a weed control benefit. Due to the remaining stubble after cutting, this option, when compared to green manuring, is especially suited to lighter textured soils where erosion can pose a problem. Once cut down the crop can be grazed or left to degrade. Degradation and return of nutrients to the soil will be more rapid if the plant material is reduced to the smallest possible size (whilst keeping in mind that some stubble should be retained on erosion prone soils). Burning of stubble is not recommended due to the loss of organic matter and nutrient while also leaving soils susceptible to erosion. However, if necessary, windrowing makes a night burn possible in situations where the paddock must be managed to suit available machinery for next season's seeding operation. Cutting can be performed with harvesting machines, slashers and windrowers. Harvesters and windrowers have the advantage of performing the cutting operation much quicker than slashers. All cutting operations should be

MANAGING FROST RISK TO MAXIMISE CEREAL YIELDS IN WESTERN AUSTRALIA *(continued)*

performed when plant material is still relatively green to stimulate more rapid degradation of plant material, trim herbicide resistant ryegrass before seed set (therefore swath, slash or harvest as low as possible) and to reduce the fire hazard.

Disadvantages

There are a couple of points worth considering when swathing and slashing. There is an accumulation of nutrients in strips through the paddock that results from a swathing operation, and the continued growth of thin strips of crop occurs when machinery tyres lay plants flat so they are not incised by slashing equipment. Cutting may also result in long straw that hinders seeding next season.

Desiccation and hay freezing

Advantages

The use of herbicides to halt crop development allows large areas to be treated in a relatively short period of time and retains the nutritive value of the crop for grazing. This nutritive value can be maintained for up to three months, depending on seasonal conditions. This not only facilitates fodder conservation but hay-making operations can take second precedence over other operations if the crop is to be cut for hay. Treatment with a desiccant halts crop development promptly. Therefore, the feed quality of the plant shoots is maintained. Herbicide resistant weeds can also be controlled, reducing the requirement for weed control next season.

Disadvantages

Despite the grazing benefits, hay freezing is expensive. The possible benefit from using this option must be weighed up against the cost. This option also results in a stubble management issue that will need to be addressed before next season.

Green manuring

Advantages

Returning plant material to the soil facilitates the retention of the nutritive value of the crop, reducing the requirement for fertiliser and trace elements next season. Nitrogen and organic matter will increase soil fertility and soil structure respectively. A wheat crop yielding 3 t/ha contains around 30-40kg/ha of nitrogen. The amount of nitrogen that will be returned to the soil can be estimated based on an estimation of crop yield before frost damage occurred. Pulse crops contain more nitrogen per unit dry matter than cereals, therefore, the resultant benefit from green manuring pulse crops is greater. Green manuring can be performed with offset disks or scalloped disc harrows. It is important that not all plant material is turned into the soil. Aim to leave around 40% of the plant material on the surface if performing this operation. This surface material acts as mulch, retaining soil and plant moisture. This results in a more rapid and efficient breakdown of buried plant material through microbial degradation. Green manuring should be performed as soon as possible in order to initiate the degradation process when the plant material still contains maximum moisture.

Disadvantages

Green manuring is not a viable proposition on light textured soils as erosion may result and leaching of the recycled nutrients is likely in the event of summer rain. The availability of suitable machinery to undertake this operation may also pose a problem to some growers. It is important that straw is reduced to a suitable size not hinder the seeding operation next season.

Standing crops

Advantages

Leaving a crop standing may be viable when going into pasture next season or where agistment opportunity arises. If the standing crop is to be grazed, the appropriate number of sheep per unit area must be considered. More dry sheep equivalents are required to graze a standing crop than pasture.

Disadvantages

Grazing standing crops may result in scouring and other problems in sheep. If a crop is left standing then the dry matter must be dealt with before a sowing operation next season.

Burning

Burning is a cheap and easy method to remove the straw for planting of next year's crop. It may also provide some weed control especially if burnt after the break of the season. However, with large amounts of bulk the potential fire hazard is a problem. Burning will result in nutrient and organic matter loss. Wind erosion before and after crop establishment will increase with no groundcover.

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CHAPTER EIGHT

WHEAT QUALITY AND THE USES OF WESTERN AUSTRALIAN WHEAT

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WHEAT QUALITY AND THE USES OF WESTERN AUSTRALIAN WHEAT

Graham Crosbie and Bill Lambe

The importance of quality in relation to wheat has been emphasized to growers in many changes that have taken place in the Western Australian wheat industry since the early 1970s.

Up to that time, Western Australian wheat had been received and marketed principally as FAQ (Fair Average Quality), the forerunner to the present Australian Standard White (ASW) (WA) grade.

Consideration of wheat quality had been mainly in relation to suitability for bread manufacture, and new varieties were assessed only for this end-product.

Recognition of Western Australia's potential to produce other wheat quality types led to the development of grades of Australian Soft (A. Soft) and Australian Hard (A. Hard) during the 1970s.

Improvement in the quality of ASW wheat resulted from the Australia-wide introduction of varietal control in 1980/81. In 1989/90, a special segregation of wheat for Japanese-style white noodles was started in this State.

These new initiatives have combined to give an increased emphasis to quality in the development of new varieties, to ensure their suitability for an expanded range of products in overseas markets. This range of products includes various pan and flat breads, steamed bread, noodles, biscuits and cakes. An important local end-use of wheat is in the manufacture of gluten and starch.

QUALITY ASSESSMENT

Many factors contribute to variation in quality among different loads of wheat. Quality potential is largely determined by the variety, but the extent to which this potential is achieved depends upon factors such as seasonal conditions, soil type and management practices.

In wheat breeding, considerable attention is given to improving the quality of varieties. Here quality characteristics such as grain hardness, grain size, milling, dough properties, and starch quality are important. In more recent times, additional varietal improvement has been sought in relation to reduced levels of black point and late-maturity alpha amylase.

At the time of receival, quality tests are carried out to measure characteristics that that are influenced mainly by the environment and grower practices – these include test weight, screenings, moisture content and protein content. Loads are also examined for the presence of stained and sprouted grain and insects.

The significance of some of the more important quality tests is as follows:

Test weight

Test weight is a measurement of the bulk density of the grain, expressed as kilograms per hectolitre, and gives a quick guide to the extent of grain filling and its potential suitability for milling to produce flour. The current receival standard for ASW and other milling grades is 74 kg per hectolitre.

Screenings

The screenings level is a measure of the amount of material which would be lost in the cleaning process prior to flour milling. The maximum level of screenings for ASW, Australian Premium White (APW), A. Soft and A. Hard is 5% by weight. Pinched grain due to a dry season, frost or disease will give higher levels of screenings. Varieties with inherently narrower grain may also give higher screenings in adverse seasons. Other contributors to screenings can include broken grain and foreign seed.

Falling Number

The Falling No is a measure of the amount of the enzyme alpha-amylase in the grain. High levels of alpha-amylase can be present due to sprouting or a condition known as late maturity alpha-amylase. The lower the Falling Number value, the higher the amount of alpha-amylase. High levels of alpha-amylase are detrimental to some end-products. Falling Number values of 300 or more are required for the main milling grades.

Black point

Black point is seen as undesirable by many wheat buyers who will not pay a premium for severely affected grain. During the milling of wheat to produce white flour, the aim is to minimise the extent of bran contamination in the flour. With black point affected wheat, a very small fraction of the blackened bran carries through into the flour. This becomes most apparent in products such as noodles and steamed buns.

Some varieties, such as Eradu and Westonia, are more susceptible to black point than others and should be avoided in high risk areas.

Moisture content

Moisture content is seldom a problem for Western Australian wheat growers as hot, dry harvesting weather usually ensures that grain is delivered at well below the maximum 12% moisture content. In some years, summer showers and high humidity have combined to delay harvesting operations in south coastal areas.

Protein content

Protein content is an important factor in determining suitability for most end-uses. It is the protein component in flour that, when hydrated by the addition of water, forms a continuous network of gluten. This network of gluten provides the structure to a loaf of bread, and depending upon the quality of the gluten, may have a substantial effect on loaf volume. Similarly, gluten provides the structure to strands of noodles, and the level of protein in the original flour has a pronounced effect on the texture or mouthfeel of the noodles after cooking.

Protein level generally varies little between varieties but is greatly affected by seasonal effects, soil type, and various management practices.

State weighted average protein levels are normally within the range 9 to 11%, with lower levels in seasons of higher average yield. (Crosbie and Fisher, 1987). In individual paddocks in most seasons, protein levels may vary substantially – in an experiment carried out in 1962 at Merredin Research Station, a protein range of 7.1-17.6% was observed in one paddock (Parish, 1963). This was associated mainly with differences in soil type and soil moisture level.

In general, higher grain protein levels occur in northern and north-eastern areas of the wheatbelt, where there is less rainfall and a shorter growing season; also in the more fertile, lower rainfall area north of Esperance. Lower protein levels are found in wheat grown in southern and western areas, consistent with a longer growing season and higher rainfall. (Crosbie and Fisher, 1987).

These protein patterns were key considerations in determining the location of receival points where A. Hard and A. Soft grades were established in the 1970s.

Eligibility for receival into the special grades of A. Hard, A. Soft and Noodle wheat depend on individual loads meeting a minimum or maximum protein standard and being of an approved variety. For the Australian Hard grade, individual loads must meet minimum standards of 11.5% for AH1 and 13.0% for AH13. In regard to Australian Soft receivals, a maximum of 9.5%% applies, with additional payments as the protein level declines to

■ QUALITY ASSESSMENT *(continued)*

8.0%. In the ASW (Noodle) segregation, acceptance depends upon protein levels being in the range 9.5-11.5%, but in some situations with "active stack management" deliveries as low as 9.0% or as high as 12.0% may be accepted.

Grain hardness

Grain hardness is determined principally by variety. It can be measured in many ways, such as by the coarseness of wheatmeal or flour, by the ease with which outer layers of the grain can be removed by abrading, by the amount of energy required or noise emitted in grinding a given weight of sample, or by the amount of damage which occurs to starch granules during flour milling.

A common method of measurement is the particle size index test, which indicates the percentage of wheatmeal passing through a fine screen – typical values for soft-grained varieties are 26 to 30, whereas hard wheats give lower values, say 12 to 16.

Higher damaged starch levels, which occur in flour produced from hard-grained varieties, result in higher water absorption levels during dough mixing and increased gassing power during dough fermentation in bread making.

Milling quality

Both variety and the environment affect wheat milling quality. High milling quality in wheat is indicated by a high yield of flour with minimal contamination by bran particles and free-flowing properties of the mill streams during the milling process. Bran contamination in the flour is indicated by poor colour grade and high ash levels, and mills normally have to conform to upper limits specified by end-users of the flour.

Dough properties

Apart from water absorption, the physical properties of the dough are important for most end-products – these properties largely reflect those of the gluten or protein component of the flour.

A common test applied in many cereal laboratories is the extensograph test which measures the elastic and viscous properties of dough while being stretched – these two properties are reported as resistance to extension (which is also a measure of dough strength) and extensibility of the dough, respectively. An adequate balance between these two properties is needed for most end-uses.

Starch quality

Since the late 1970s, attention has been focused on quality variation in the starch component of flour, and this has been found to be of significance of certain products, particularly noodles. Critical factors influencing starch quality include the ratio of the key starch components amylose and amylopectin. Starch quality can be measured in a number of ways, including the extent of swelling by starch or flour when gelatinised or by paste viscosity tests.

QUALITY REQUIREMENTS FOR VARIOUS END-USES

Good milling quality and soundness of the grain are common requirements for all end-uses. In regard to other criteria however, specific qualities are needed for different end-uses.

For loaf bread, hard wheat is generally preferred to give sufficient damaged starch levels to ensure adequate water absorption in the dough and a high moisture content in the loaf, and to give good gassing power during dough fermentation. Loaf volume is increased with higher protein content, but only if combined with strong, extensible dough properties – these are needed for retention of carbon dioxide and moisture vapour during fermentation and baking, and to give a satisfactory crumb texture.

Flat bread is preferably made from a hard wheat, with moderately high protein content, high water absorption, medium dough strength and adequate extensibility.

Steamed bread and buns are popular in many Asian countries, and are made from flour milled from medium to moderately high protein hard wheat or low protein soft wheat according to type. Low levels of yellow pigment are required in the flour to produce a suitably white product.

Various qualities are needed for different types of noodles. The Japanese-style white salted noodle or udon, important to Western Australia wheat producers, requires an essentially soft-grained wheat of about 10.5% protein, having moderately strong dough properties and starch with high swelling properties. Low ash level is a very important consideration in the manufacture of flour for noodles in Japan, particularly to ensure good noodle brightness. Moderate levels of yellow pigment in the flour are needed to give the desired creamy noodle colour. Generally higher wheat protein levels are needed for alkaline noodles – about 13.0% is needed for Japanese ramen and about 11.5% for the Hokkien style noodle of S.E. Asia.

Low water absorption flour, made form low protein soft wheat, is preferred for the manufacture of sweet biscuits. Weak, inelastic dough properties are also needed to allow the biscuit to spread sufficiently during baking. Cake flours are also made from this type of wheat, usually from selected high quality flour streams, and may include a chlorination treatment.

■ WHEAT QUALITY TRENDS IN WESTERN AUSTRALIA

Until the 1950s, most of the wheat varieties grown in Western Australia were soft-grained and had weak dough properties. This wheat was received into only one milling grade – Fair Average Quality (FAQ). The emergence of the hard wheat Gabo in the 1950s had a substantial effect in increasing the hardness, dough strength and breadmaking quality of Western Australian FAQ. (Crosbie, 1988).

Gabo's effect was partially offset by Insignia, also popular at this time, which was cast more in the mould of the earlier weak, soft-grained wheats such as Nabawa and Bencubbin.

Following the rust epidemic of 1963, there was a rapid growth in popularity of Gamenya, which proved so well adapted that it was the leading variety in Western Australia for 21 years from 1965/66 to 1985/86. Gamenya was unique in combining the soft grain character with moderately high dough strength, which assisted in maintaining the quality of FAQ.

Development of new wheat grades

After the introduction of Gamenya, a wider range of quality types was sought. This was in response to an improved understanding of market requirements and the recognition of new opportunities for the marketing of Western Australian wheat. Important developments in the 1970s were the breeding of Tincurrin wheat and the introduction of the A. Soft grade, allowing new markets to be developed in Malaysia and South Korea. Other key developments in the 1970s were the breeding of Madden wheat and the development of the A. Hard grade. The introduction of a separate noodle wheat segregation in 1989/90 and the release of the noodle variety Cadoux in 1992 were other important milestones.

Development of Australian Soft and Australian Hard grades

The segregation of A. Soft was intially based on the variety Egret, but quickly switched to Tincurrin following the release of this high yielding variety in 1978 (Reeves et al 1978). Since then, newer varieties such as Corrgin and Datatine have contributed to this grade.

The A. Hard segregation was based initially on the varieties Gamenya and Falcon, but neither of these varieties has the quality now required for this grade. Significant varieties of higher milling quality and with a more suitable combination of grain hardness and dough strength were Madden (released in 1974), Bodallin (1982), Gutha (1983) and Wilgoyne (1989). More recent releases include Amery (1993), Cascades (1994), Carnamah (1996) and Kalannie (1996).

Development of a noodle wheat segregation

During the 1970s, ASW wheat from Western Australia became recognised as having excellent quality for Japanese white salted noodles or udon. This largely reflected the starch quality of Gamenya, the leading variety in Western Australia from 1965 to 1985 (Crosbie et al 1990). While production levels of Gamenya in Western Australia remained high, so did the quality of ASW for udon. However, during the 1980s there was a marked change in the quality of the ASW mix, as growers replaced Gamenya with higher yielding varieties which, although suitable for other end-uses, were of poor quality for noodles. This was partly offset by the emergence of Eradu, a variety of similar quality to Gamenya. By 1988/89, the combined sowing of Gamenya and Eradu had dropped to an alarming level, representing only 17% of the total wheat area – this was down from 44% in 1983/84 (Crosbie, 1990). This had made it increasingly difficult to ensure sufficient levels of these key varieties in shipments to Japan. It had also become difficult to meet the protein requirement of the Japanese market – 10.5% – because there were fewer receival points with sufficient Gamenya and Eradu from which to select.

Following considerable industry debate, a segregation based on the varieties Gamenya and Eradu was commenced in 1989/90. This concentrated the dwindling supplies of these key varieties which ensured an adequate percentage of these wheats in shipments to Japan. The introduction of separate pooling for noodle wheat in 1992/93 provided market-based premiums which helped to offset the differential in yield between noodle wheat and alternative varieties. This also provided much needed time to develop higher yielding noodle wheat varieties to enable growers to take full advantage of Western Australia's market lead in the production of this wheat type.

Noodle research at Agriculture Western Australia proved vital in the development of new noodle wheat varieties Cadoux in 1992, and Arrino and Calingiri in 1997 (Crosbie, 1997). The research included:

- The introduction of a visiting experts program involving Japanese noodle technologists
- Recognition of the importance of starch swelling properties on noodle texture and the development of the Flour Swelling Volume test at Agriculture Western Australia, for use in selecting for starch quality in early generation breeding lines (Crosbie, 1991; Crosbie et al, 1992; Crosbie and Lambe, 1993).
- Recognition of substantial variation in noodle colour stability among Australia wheat varieties (Crosbie et al, 1994). This lead to the development of rapid screening tests and incorporation of improved colour stability in new varieties.

■ BLACK POINT

Fran Hoyle

Black Point is identified primarily as a dark discolouration of the surface tissue located at the germination-end of wheat (Figure 8.1), but may range in extent and severity depending on cultivar and season. Early research associated symptoms with the presence and subsequent infection of grain by field fungi (Alternaria spp.), during normal development and maturation. Recent studies however, have been unable to provide conclusive evidence in the implication of fungi, the development of black point largely affected by environment (see Chapter 7).

The presence of this grain disorder is normally not observed during plant growth, but is only apparent once grain is harvested. It affects only the appearance of the grain and is not associated with other leaf or root diseases. Receival standards currently allow a maximum 5% of 'stained or black pointed' grain in premium segregation's, or 25 grains per 500 grain sample.

Figure 8.1 – Sympomatic expression of black point in wheat

Seed Quality

Grain affected by black point has commonly been associated with a reduction in the germination capacity and vigor of grain used for seed, where pathogenic fungi are present. In Western Australia, black point does not usually have any significant detrimental effects on seed germination or emergence, and does not appear to increase in stored grain under optimal storage conditions. Seed germination may be lower where severe symptoms are expressed, and germination tests are recommended prior to storage and seeding, where rates may be adjusted if required.

Grain Quality

The inherent quality of wheat grain associated with black point is observed to be largely confined to a discolouration of the grain and is not normally associated with reductions in flour quality, grain protein or viability. Grain quality is only slightly affected, marketability being most affected by the development of black point.

Severe black point can lower grain quality and interferes with the milling and baking properties of the grain. Milling wheat grain with severe staining at a lower extraction rate, can increase the quality of flour produced from stained grain, but will cause a loss in flour and semolina yield and may still produce a darker colour flour. Where flour discolourisation is observed, the quality of end products such as pasta, noodles and semolina can be seriously affected, lowering their marketability. Lower levels of black point and localised discolourisation may be removed during milling and do not represent a significant reduction in grain quality. Black pointed grain is commonly associated with a larger seed size and higher grain weight. Grain protein is generally not influenced by the presence of black point.

■ ON-FARM QUALITY ASSURANCE

Nicole Kerr
Quality Coordinator – Grains Agriculture Western Australia

Many users of grain now demand that the grain they purchase meet prescribed quality standards, are free of chemical residues and have been handled in a way to ensure they are safe to eat. Quality assurance systems allow growers, and other businesses in the food supply chain, to demonstrate that they meet all of their customer's requirements.

Quality assurance programs can offer benefits to grain producers in two ways: firstly, through productivity gains due to good management practices; and secondly, through marketing advantages such as being a preferred supplier, attracting new markets or alternatively holding existing markets against competitors.

Both market pressures and legislative requirements are driving the Australian grains industry towards embracing quality assurance.

Market pressures

Demands for assurances from end-users of grain are increasing. More flour mills are becoming quality assured, and their quality assurance systems are putting pressures on suppliers of the raw ingredient, wheat. There is also an increasing awareness in some markets to chemical residues in grain. For example, wheat destined to South Korea has to be tested for over 100 different chemicals. A few years ago this number was 38. A major flour mill in Japan carries out their own additional chemical testing on wheat they use.

Wheat producers in other countries have started to implement quality assurance systems on-farm. In the United Kingdom, a quality assurance program covers one third of the crop, and in 1998, maltsters did not issue contracts to growers that were not quality assured. In Canada, the federal government, in partnership with national producer organisation, has developed the Canadian On-Farm Food Safety Program. This has started in the meat industries, but is expected to move into grains in the near future.

All of these activities put pressure on Australian wheat producers to adopt an on-farm quality assurance system.

Legislation

Australians consume over 20 billion meals every year. Of these, it is estimated that less than 0.02% result in food borne illness. Nevertheless, this equates to about 4.2 million cases of foodbourne illness every year in Australia.

Consumers now expect a guarantee of safety when it comes to food, and many governments have introduced food safety legislation to ensure food is safe to eat. This in turn has encouraged the adoption of quality assurance programs.

in Australia, the New Zealand Food Authority (ANZFA) has proposed the National Food Hygiene Standard. This will apply to all food businesses including most primary producers.

Low risk businesses in the primary industry sector will not have to meet the requirements of the food safety standards. Grain production is expected to be classified low risk, and this will be revised in 2002. However, medium and high risk primary industry sector operations which do not have an independently audited food safety program in place would be expected to develop one as the food safety standards are implemented.

Quality Assurance

Both customers and legislation are encouraging producers to adopt quality assurance systems. So what is quality assurance? Quality assurance is simply a formalised system in which you say what you are going to do, do what you say and then prove it. Planned procedures are put in place before production to ensure customer requirements are met (often both food safety and product quality requirements). For example, many buyers of our wheat are concerned with the level of chemical residues in grain. In order to avoid residue problems, and hence not meet our customers requirements, the following measures are put in place; only use registered chemicals at recommended rates, observe witholding periods, calibrate equipment before use and use trained staff.

Records need to kept and audited regularly, usually by an independent auditor, to give the system integrity. This provides the 'proof' that you have been following your quality assurance system, and your customers can have confidence that you are supplying product that meets specifications.

There are a number of different quality assurance systems in the market place. These include branded quality systems like Great Grain, Cattlecare, Flockcare and Dairy first. SQF 2000CM is a quality code that has been developed by Agriculture Western Australia specifically for the food industry and is not commodity specific like the branded systems. It incorporates HACCP (Hazard Analysis Critical Control Point) which is a risk management tool for use in the food industry that has international acceptance. The ISO 9000 series is another internationally recognised quality assurance code that is not specifically for the food industry, but rather is used across a range of industries.

Quality assurance systems offer benefits to growers as outlined earlier, however there are also costs associated with these systems. Indirect costs include time spent training staff, completing spray diaries, inspecting equipment; inputs such as those spent on pest management programs and the cost of product not meeting premium segregation standards. Direct costs include auditing and system development costs.

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CHAPTER NINE

TILLAGE

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■ TILLAGE - A BRIEF HISTORY

Ron Jarvis

Until the 1970s Western Australian farmers did not question the need for cultivation as a necessary part of wheat farming. Cultivation was considered essential to:

- Kill weeds;
- Prepare a seedbed;
- Aerate and loosen the soil for better root growth;
- Mineralize soil nitrogen and other nutrients to a plant-available form; and
- Control root disease.

Nevertheless, most Western Australian farmers still cultivated less than Australian and world standards.

Disc ploughs, which had replaced the mouldboard ploughs of earlier years were declining in favour of tined scarifiers and chisel ploughs as the main implement for primary cultivation. Rather than relying on complete soil inversion and burial for the initial weed kill, the tined implements were used to break soil-root contact, promoting weed desiccation rather than complete burial.

The newer implements were wider and could be operated faster, allowing larger areas to be sown quickly and with less labour. Subsequent cultivations, usually shallower than the primary operation, were carried out at intervals before seeding, to kill new weed germinations, uproot transplants and break down the seed bed to a fine tilth before seeding.

The clover ley farming system introduced in the late 1940s had placed more emphasis on rushed pre-seeding cultivations compared with the long nine-month fallows previously used for wheat crops.

Chemical weed control (2,4-D, MCPA) for some in-crop broadleaved weeds was available, effective, and relatively cheap. Other chemicals became available for broadleaved weed and wild oat control in the 1960s but were generally considered expensive.

Cultivations from the break of the season up until, and while seeding, were considered essential for successful wheat cropping.

The non-selective, non-residual desiccant herbicides paraquat and diquat discovered in the 1950s and first sold commercially as Spray.Seed® in Western Australia in 1972 were the catalysts for the 'minimum tillage revolution'.

Initial commercial efforts to sell the concept of minimum tillage were based on the value of additional grazing made available by deferring the first cultivation of pasture paddocks.

Reduced erosion was a benefit but it was hard to evaluate its worth.

Although there were a few enthusiastic adopters, the system was unpopular because of the difficulty in controlling ryegrass in the crops established with one spray and no subsequent cultivations.

Trifluralin, introduced in 1974, was rapidly adopted as a cheap method of ryegrass control, although it failed to decrease, and sometimes increased, cultivation because of the need for incorporation of the chemical into the soil.

Half a million hectares were sprayed with trifluralin in 1978, compared with less than 50,000 ha sown with Spray.Seed® and reduced tillage.

By 1983 both systems were being used on about one million hectares.

The rapid rise in acceptance of crop establishment via minimum tillage and dependence on a 'knockdown' herbicide was promoted by the introduction of Hoegrass® in 1978, for post-emergence ryegrass control, and the use of cheap and effective in-crop broadleaved weed control by mixing diuron with MCPA or 2,4-D.

Direct-drilling was the term coined for the system which relied on these herbicides to control all weeds and used only one cultivation to sow the crop.

In 1977, following increasing concern over soil conservation, the then Department of Agriculture established 11 long-term experiments to compare reduced and zero tillage with the conventional crop establishment practices using numerous cultivations. Crop growth and yields, and soil properties were measured between 1977 and 1995 and the results were used to derive the tillage strategies shown later.

The recent revival of no-tillage practices started around 1990 when only a few farmers direct drilled with narrow points. The development of the use of the hard wearing material, tungsten carbide, allowed increased adoption to around 2% of Western Australian farmers with tine systems and around 1.5% had no-till discs systems by 1993. The benefits of earlier sowing to retain the moisture from no-till were an important factor as well as being relatively inexpensive to convert to the new system. The earlier research work was drawn upon to include the deep dig principle (with tines or coulters) and fertiliser separation from the seed to reduce fertiliser toxicity in the narrow slots as more of a standard for the new no-tillage principle. Both this and the inclusion of a low disturbance deep-rip required on deeper yellow sandplain resulted in adoption of around 15% by 1996 and around 40% by 1998. Chemical use has also increased and with herbicide resistance increasing, the option of full soil disturbance may still be useful but only when necessary for factors such as weed control or trace element fertiliser incorporation.

The ideal tillage strategy is one that controls weeds, maintains soil structure, will not cause erosion, controls root disease, allows early sowing, establishes good plant density with early vigorous growth, gives the greatest yield, and is cost effective.

No single system is likely to be ideal for all soils and situations, but the following sections will help producers develop conservation-conscious tillage systems that will maximize yield and nett returns for their particular farms.

SUMMARY OF TILLAGE STRATEGIES

Ron Jarvis

Fine-textured soils

The fine-textured soils include the salmon gum-gimlet soils of the eastern wheatbelt and the widespread 'grey clay' and moort soils.

Characteristics

Surface structure degrades rapidly under cultivation, leading to slaking and crusting.

Tillage strategy

No-till or direct-drill. Reduce cultivation to a single working, and use gypsum if necessary to establish a one pass system.

Loams and gravelly loams

Characteristics

Not responsive to cultivation.

Tillage strategy

Can be successfully no-tilled or direct-drilled.

Yellow earths and earthy sands

The extensive deep yellow sands found throughout the central, eastern and northern wheatbelt.

Characteristics

Form hard-setting surface crusts. These soils pack hard under the influence of rainfall and are highly responsive to cultivation. Dry cultivated soil is at risk of wind erosion.

Tillage strategy

Soil disturbance is necessary for maximum yields. No-tilling or direct-drilling lowers yield, however this may be minimized by additional deep cultivation during the seeding operation. Deep ripping increases yield.

Yellow earths with acid subsoils

Soil acidity on the yellow earths is a particular problem throughout the eastern and north-eastern wheatbelt.

Characteristics

Hard-setting surfaces and highly acidic subsoils.

Tillage strategy

No-till or direct-drilling can be used as sub-soil acidity negates any advantages obtained from cultivation.

White sands

Characteristics

Coarse-textured grey and white sands. These do not form surface crusts and are susceptible to wind erosion. Rhizoctonia bare patch may be a problem.

Tillage strategy

Reduced cultivation is essential to reduce the risks of wind erosion. Cultivation below the seeding depth reduces rhizoctonia bare patch.

■ SANDY-SURFACED SOILS

Sandy-surfaced soils cover most of the wheatbelt of western Australia. They range from coarse textured deep white sands to the yellow earths and yellow earthy sands – 'good sandplain' – soils found in the northern and central wheatbelt.

Research, as well as farmer experience, has found that wheat crops direct-drilled on sandplain soils grow more slowly than crops sown after cultivation and are usually lower yielding.

The effects of cultivation

Cultivation of a sandy-surfaced soil:

- Improves soil structure;
- Increases yield; and
- Decreases some diseases.

Soil structure

Sandy soils have a 'massive' structure and do not form stable aggregates such as are found on well-structured heavy soils. Under the impact of rainfall and traffic each season, the sand grains in the surface soil pack together forming hard surface layers with high soil strength.

Without a cultivation, root growth is impeded in the surface, reducing early plant vigour and lowering grain yield.

Cultivation of the sandy surfaces increases porosity – 'opens' the soil – and allows greater mineralization of nitrogen. Roots grow more vigorously in the porous surface soil and nitrogen and soil water is used more efficiently.

Yield

In the absence of cereal root disease or other problems, cultivation has given an average eleven% yield increase over direct-drilling from more than 200 Agriculture Western Australia experiments. Results from a continuous cropping experiment at Wongan Hills been typical (Table 9.1).

Table 9.1 – Wheat yield averaged over ten years of continuous wheat cropping on yellow loamy sand at Wongan Hills. All treatments were sown on the same day and nitrogen applied 2 to 3 weeks after seeding. All treatments were weed free.

	Wheat yield (t/ha)		
Nitrogen (kg/ha)	**Direct-drill (triple disc drill)**	**Direct-drill (combine)**	**Scarify twice own with a combine**
0	0.74	1.02	1.29
50	1.26	1.51	1.72

The advantage of cultivation over direct-drilling with a combine has averaged 0.27 t/ha over ten years and the application of nitrogenous fertilizer has failed to remove the yield advantage of the cultivated seedbed. The very poor yield from the 'zero-disturbance', triple disc drilled treatment emphasizes the requirement for cultivation for best yield on sandplain soils.

Disease

Rhizoctonia bare patch, which may be found throughout the wheatbelt, but which is a particular problem on the Esperance sandplain, is reduced by cultivation.

The case for reduced tillage

While cultivation has increased grain yields on sandy-surfaced soils, there are important reasons why cultivation is not desirable. Some of these are:

- Increased risk of wind erosion;
- Loss of organic matter;
- Delayed time of seeding;
- Increased weed germination as weed seeds are brought to the surface with cultivation; and
- Poorer pasture re-establishment after a crop.

Of paramount importance is the increased risk of wind erosion of cultivated surfaces. The fine sands of the West Midlands and the south coast, and the yellow sands of the Eradu sandplain are particularly susceptible to erosion as they dry within hours of cultivation and do not form surface crusts.

An advantage of reduced cultivation is better clover regeneration in the year following the crop. Clover regeneration depends on the extent and depth of burial of the burr during tillage. Reduced tillage systems leave more burr at a shallow depth suitable for good germination.

At Avondale and Esperance (Table 9.2), direct-drilling with a triple disc drill, which causes virtually no surface disturbance, has consistently given the best clover re-establishment, the next best was direct-drilling with a combine. Where paddocks have been scarified before seeding, burial is presumably greater and re-establishment poorer. Ploughs would be expected to be worse.

Table 9.2 – Effect of tillage method on sub. clover regeneration

Crop establishment method	Clover (plants/sq.m)		
	Avondale 1983	**Avondale 1985**	**Esperance 1985**
Triple disc drill	314	394	318
Direct drill combine	215	368	56
Scarify twice	137	136	29

■ QUALITY REQUIREMENTS FOR VARIOUS END-USES.

Tillage strategies for sandy soils

Development of the cultivation-depth-modified (CDM) combine provides an alternative to conventional tillage systems for sandy soils.

Cultivating deep only in narrow furrows below the seed gives a less intensive surface disturbance, but appears to loosen the soil sufficiently where it counts, to overcome the detrimental effects of direct-drilling. This reduced disturbance makes the surface less prone to wind erosion, however, sometimes at a cost of more herbicides, because of the lack of 'second knock' effect of wide points.

The experimental CDM combine has the front cultivation tines in line with the rear seeding tines, with variable depth possible relative to each other. Thus the front tines could cultivate level with the seeding tines, or cultivate 2, 4, 6, 8, or 10 cm below where the seed and fertilizer would be drilled in the same pass.

In two experiments at Merredin (1986) and Wongan Hills (1987), grain yield was directly related to soil strength (see Figure 9.1). Soil strength was varied by tillage treatments including several depths of working using the CDM combine, separate operations of scarifying, as well as deep ripping at two depths.

From twelve experiments throughout the State, direct-drilling with the modified combine produced an average 360 kg/ha better than one scarifying.

Most of the work was on the erosion-prone Esperance sandplain on Esperance Downs Research Station where the machine overcame the direct-drill problem of rhizoctonia bare patch. The results are summarized in Table 9.3.

Table 9.3 – Effect of cultivation on rhizoctonia bare patch and wheat yield

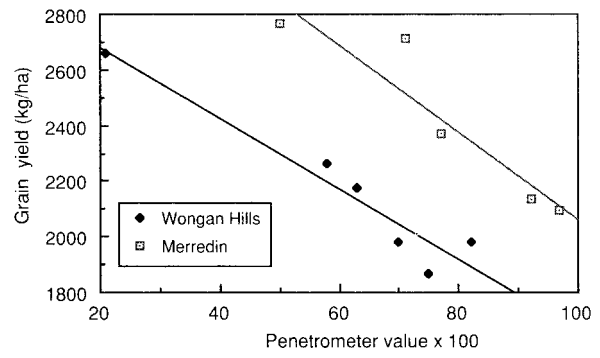
	Direct-drill (combine)	Direct-drill (cultivation-depth-modified)	Scarify twice sown with a combine
% diseased	20.4	4.30	5.10
Wheat yield (t/ha)	2.93	3.70	3.63

The CDM combine has shown advantages over scarifying mainly in years with a wet start when nitrogen, made available following scarifying, is leached. The narrow slot machine appears to provide an each-way bet: it increases available nitrogen in the slot by tillage but leaves the between-slot area to release its nitrogen normally.

In a Wongan Hills experiment in 1987 on yellow Wongan loamy sand which had been in a lupin/wheat rotation for several years, rhizoctonia was not evident.

Direct-drilling with the modified combine yielded 2.8 t/ha compared with the normal combine at 2.3 t/ha and the scarified treatment at 2.7 t/ha. The yield increase represented 82kg/ha for every centimetre that the front tines of the modified combine cultivated below the seed depth, that is, yield was 820 kg/ha better at the machine's maximum tine difference setting of 10cm.

Figure 9.1



Cultivation lowers soil strength and increases grain yield on sandy soils at Wongan Hills and Merredin.

The extra fuel used by having narrower points 13cm deep compared with wide points at seeding depth, was only 1.5 litres/ha.

Results, from six direct-drilling experiments where different depths of cultivation below the seed were tried, averaged an extra 62 kg/ha grain for each centimetre that the cultivation tines worked below the seeding tines.

These experiments confirm the concept that lowering the soil strength beneath the seed allows wheat crops to be direct-drilled on sandy soils without losing yield. Some seeding machinery already allows cultivation below the depth of seed placement, however further machinery development is required to optimize point size, cultivation depth and row spacing.

■ LOAMS AND GRAVELLY LOAMS

Unlike sandy soils, red loamy soils of the Avon Valley do not respond to cultivation. Even a zero-disturbance triple disc drill produced yields equal to or better than cultivation, especially when adequate nitrogen is applied (Table 9.4).

With no benefit evident from cultivation of these soils, the system of lowest cost and best erosion prevention can be employed.

Table 9.4 – Wheat yield averaged over ten years of continuous wheat cropping on red-brown loam at Avondale Research Station. All treatments were sown on the same day and nitrogen applied 2 to 3 weeks after seeding. All treatments were weed free.

	Wheat yield (t/ha)		
Nitrogen (kg/ha)	**Direct-drill (triple disc drill)**	**Direct-drill (combine)**	**Scarify twice own with a combine**
0	2.03	2.20	2.29
60	2.81	2.77	2.69

FINE TEXTURED SOILS

One of the limitations to crop production in the wheatbelt is the poor structure of fine textured soils.

Many years of fallowing and cultivation have caused the loss of soil organic matter and the breakdown of the soil aggregates that are essential to maintaining a stable soil structure. This deterioration can decrease yield by more than 50%.

Inappropriate tillage regimes are the primary cause of the structural breakdown.

About 3.5 million hectares of the State's agricultural soils are susceptible to this form of soil degradation. These include the red-brown earths and red duplex soils (salmon gum and gimlet soils) common in the eastern and central wheatbelt, and the grey or moort clays of the south-western wheatbelt (around Narrogin, Katanning and Lake Grace).

The signs of degraded soil structure

There is a rapid decline in the physical condition of fine textured soils when they are cleared and cropped.

- The soil surface sets hard when dry.
- Infiltration of rainfall is slow and water ponds on the surface during rain. Ponded water becomes cloudy from dispersed clay particles and remains on the surface for days or weeks after rain.
- Tillage is difficult. The soil is too hard when dry, but becomes slippery after only a few millimetres of rain. Cultivation is only possible for a few days before the soil again becomes too hard to work. (They become 'Sunday soils'.)
- Crop emergence is patchy because the tilled soil slakes and seals after rain, drying to a hard crust which is difficult for seedlings to penetrate.

The importance of soil structure

The collection of soil particles into larger units or aggregates gives the soil its structure. The formation of these units produces pores both within and between the aggregates allowing infiltration of water and air into the soil, which is vital for good plant growth. It is important that these aggregates remain stable to maintain the pores.

The higher the clay content, the more important is soil structure. In a well-structured soil the clay particles are bound together to form micro-aggregates. Soil aggregates are then formed by these micro-aggregates binding with silt and sand particles.

The soil particles are bound into aggregates by the soil organic matter, by electrostatic forces, that is, the attraction of positive and negative charges, and by fungal hyphae, bacterial gums, fine plant roots and cementing agents such as iron or aluminium oxides.

Together with organic matter, the electrostatic forces bind particles together to form the micro-aggregates, while organic matter, and fungal hyphae bind the larger aggregates.

How is the structure made unstable?

The structure of the soil is broken down when the amount or the strength of the binding agents is reduced by disruptive forces breaking the aggregates into their constituent parts. These disruptive agents are the mechanical action of cultivation and traffic, the impact of raindrops on the surface and trampling by animals.

Of these, cultivation is the most important cause of declining soil structure. Cultivation:

- Decreases soil organic matter by promoting its breakdown. The improved aeration of the soil when it is tilled promotes more rapid microbial breakdown of organic matter, reducing the amount of binding agents in the soil.
- Mixes soil organic matter through the cultivation layer, diluting it throughout the top 8 to 10 cm of the soil.
- Breaks the important bonds, which, over time, have been formed in the soil by the organic matter. Once broken, the continual disruption of the soil through cultivation prevents these bonds from being re-formed. Soil aggregate bonds are also weaker when they are wet and thus a wet soil is more susceptible to disruptive forces than a dry soil.

The result of cultivation is therefore less organic matter forming fewer bonds; and those, which are formed, are less able to maintain a stable structure. The soil then becomes much more susceptible to disruptive force – such as raindrops – that will break down aggregates and cause the soil to slake.

Management of fine textured soils

Tillage

Minimizing tillage, consistent with good crop establishment, is the key to the management of fine textured soils for crop production. The rationale behind reduced tillage is to slow the destruction of organic matter, and to reduce the disruption of the binding materials, which maintain a stable soil structure.

Most of our knowledge about managing fine textured soils comes from a long-term experiment established at Merredin on a red-brown earth originally carrying salmon gum and gimlet vegetation. Four crop establishment systems were used and the site was continuously cropped to wheat using the same tillage treatments from 1977 to 1995.

Tillage treatments tested, in increasing order of soil disturbance, were:

- Direct seeding with a triple disc drill;
- Direct seeding with a standard combine;
- One cultivation with a scarifier followed by seeding with a triple disc drill;
- The district practice method of the time. This was a scarifying, followed by another working with a scarifier, and seeding with a standard combine. In some seasons an extra working was required for seedbed preparation.

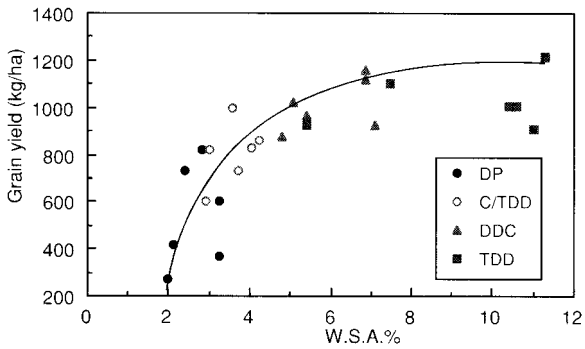
■ FINE TEXTURED SOILS *(continued)*

Weeds were controlled with knockdown and post-emergent herbicides.

Soil samples were taken five centimetres deep from each plot from 1981 onward and tested for water-stable aggregate percentage (WSA) which is the percentage of aggregated material remaining on a two millimetre sieve after sieving in water. The higher the WSA, the more stable the soil when wet. A stable soil is less prone to crusting and setting hard, and allows rain to infiltrate faster.

Tillage treatments influenced WSA percentage significantly every year. The district practice treatment produced a less stable soil structure than the other treatments, while the triple disc drill produced the least soil disturbance and improved structure the most (Figure 9.2).

Figure 9.2



The relationship between soil structure (measured as % water stable aggregates) and grain yield on a red-brown earth (Salmon gum) soil at Merredin.

The wheat yields for the four tillage methods averaged over the same six years are shown in the first column of Table 9.5.

In the early years, the treatment which had been direct-drilled with a combine each year produced an average yield of 590 kg/ha/year or 75% more than the cultivated district practice where soil structure was poor.

In 1987, the district practice treatment – two scarifications plus sowing with a combine – was changed to direct-drilling with a combine. Grain yields immediately improved. Over the three years 1987 to 1989, the once poor yielding cultivated soil averaged 1.42 t/ha compared with the long-term direct-drilled treatment yield of 1.33 t/ha.

The impact of cultivation on the structural breakdown of the soil will depend on the soil type, soil moisture during cultivation, and the environment (through effects on plant growth). Tillage regimes therefore should be tailored for specific situations. Experience has shown that even where yields are not affected in the short term, excessive cultivation of fine textured soils will degrade the soil.

Pasture

There are other practices which promote a stable soil structure.

Pasture increases the return of organic materials to the soil, and promotes the proliferation of soil animals and fungal activity. A pasture phase provides a spell from cultivation and soil aggregation increases. Fertilizer application on pasture increases plant growth and soil organic matter, however, trampling by animals can reduce soil structure.

Table 9.5 – The effect of tillage and gypsum on wheat grain yield. In 1987 the triple disc treatment was changed to direct drill 50 mm points, scarify then triple disc to scarify then 50 mm points and the district practice to direct drill with combine.

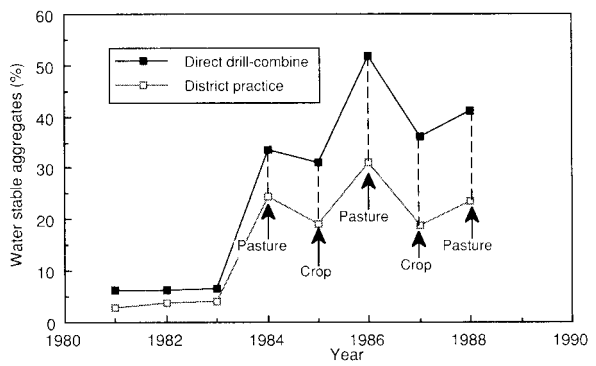
Tillage treatment since 1977	Yield (t/ha)				
	1981 to 1986 no gypsum	1983 to 1986 no gypsum	1983 to 1986 gypsum	1988 to 1995 no gypsum*	1988 to 1995 gypsum*
Triple disc drill (TDD)	1.27	1.35	1.51	-	-
Scarify, then TDD	1.21	1.29	1.47	-	-
District practice	0.79	0.92	1.36	-	-
Direct drill with combine	1.38	1.47	1.53	1.63	1.74
Direct drill narrow points	-	-	-	1.76	1.79
Scarify then narrow points	-	-	-	1.56	1.66

* average of the five wheat crops during 1988 to 1995 (gypsum treatment applied 1983).

■ FINE TEXTURED SOILS *(continued)*

Figure 9.3 illustrates how soil structure (as measured by WSA percentage) improves in the pasture year, but are reduced when cropped. The data are from an experiment adjacent to the continuously cropped one reported in this paper.

Figure 9.3



Water stable aggregates increase under pasture and decrease when the soil is cultivated for a crop.

Introducing a pasture phase may be essential in some situations because organic matter levels continue to decline on some soils supporting continuous wheat, even with minimum tillage.

The role of gypsum

Although reducing cultivation can delay or reverse soil structural decline and increase grain yields, the return to productivity can sometimes be slow. On some soils, application of gypsum – calcium sulphate – can hasten the rate of improvement when used with reduced tillage.

Gypsum improves soil structure by reversing the dispersion of the clay particles, making the soil aggregates more stable when wet and the soil surface more friable when dry.

Dispersion is the process whereby individual clay particles migrate away from each other because the electrostatic forces repelling them are greater than those attracting them.

The dispersed clay particles may then clog pores, which will impede infiltration of water. Also, when the soil dries, the clay particles act to cement the soil constituent together forming a characteristic surface crust.

The calcium in gypsum replaces sodium on clay particles allowing them to stay together (flocculate) which is the basis of a more stable soil structure.

Table 9.5 shows the increase in yield averaged over 4 years (1983 to 1986) from a single application of gypsum in 1983 for the degraded district practice treatment. By comparison, there was little grain yield response where the soil structure was good following years of direct-drilling.

Unfortunately not all dispersive clays respond to gypsum because other factors, such as the concentration of the soil solution, also control the response. Some laboratory tests give a reasonable guide for predicting the response of a soil to gypsum.

The aim of gypsum application is simply to prevent clay dispersion. It does not in itself provide stable soil structure. It is important to first determine if a soil will respond to gypsum. If it will, the gypsum application must be supported by minimum soil disturbance and other practices which will promote organic matter build-up and aggregate binding, necessary to achieve a stable soil.

Further reading

Farmnotes

57/90 Identifying gypsum-responsive soils. (Agdex 514).

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■ DEEP TILLAGE

Ron Jarvis

Deep tillage – deep ploughing, subsoiling or deep ripping – involves disturbing the soil below the normal cultivation layer, often to 40cm without inverting the soil. It breaks up traffic-induced, or naturally occurring compacted layers.

The practice was almost unknown in cereal production areas of southern Australia, although research on deep ripping dates from the 1890s. Some small yield increases were recorded but were not enough to encourage the practice.

On a worldwide basis it is only in exceptional situations that deep tillage has increased crop yields in semi-arid areas.

In the early 1980s, experiments with deep ripping in Western Australia demonstrated spectacular improvements in wheat yield. In 1981, two experiments at Wongan Hills and Yorkrakine gave 600 kg/ha more grain when a loamy sand was ripped to 30cm.

This stimulated research into deep ripping as a soil management practice. Results have shown that compaction pans are widespread on the deeper sandy soils; and that disruption of the pans can give large yield increases.

Traffic pans

Compaction pans which restrict cereal growth exist on virtually all soils which texture loamy-sand or sandier. These represent an area of 6.6M ha or 48% of the agricultural area of Western Australia (McFarlane 1984) without including the 5.2M ha of the sandy surfaced duplex soils which exhibit compaction pans if there is sufficient depth to clay. These coarse-textured sandy soils generally have a variety of particle sizes which are compacted when moist by machinery travelling over the surface.

The weight per unit area (pressure), total axle load and the number of machine passes affect the strength and depth of the soil compaction. Wheel slip also increases compaction, but to a lesser extent.

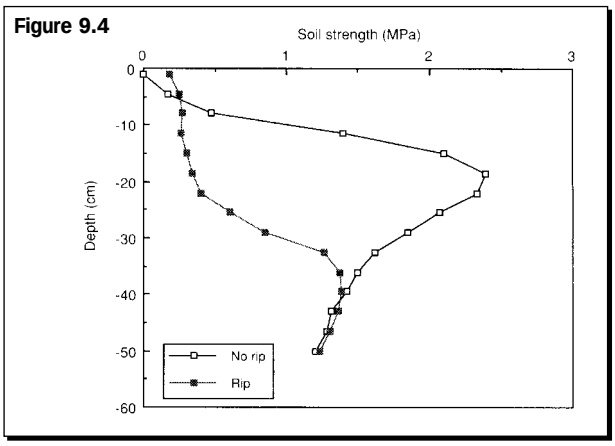
Traffic pans restrict root growth, reducing plant uptake of water and leachable nutrients such as nitrogen. Eight weeks after seeding at Wongan Hills wheat roots were 30cm deep on unripped ground compared with 90 cm deep where deep ripping had removed the traffic pan.

Wheat roots will eventually penetrate an unripped pan, but do not go as deep, resulting in less plant dry matter production and grain yield. In the above example, wheat on the unripped area yielded 600 kg/ha (25%) less grain.

The depth of the compacted layer depends on soil type. The lower the clay content of the soil, the deeper the hard layer.

On loamy sand and yellow earth such as at Wongan Hills (Figure 9.4), which have 10 to 12% or more clay, the compaction layer has maximum strength at about 20cm depth.

Figure 9.4



Soil strength profiles for a yellow loamy sand before, and following ripping to 30 cm, Wongan Hills, 1986.

Yellow sands and earthy sands such as Eradu sandplain have 4 to 8% clay and the hard pan is about 25 cm deep.

Deep white sands with little clay have a pan at 30cm or more.

However, white sands with no apparent pan – the soil strength keeps increasing with depth – have also shown crop responses to deep tillage.

Factors affecting the response to deep ripping

Deep ripping has proved extremely beneficial only on light sandy soils. Even on these soils in the medium rainfall area, yield responses to ripping have been variable. If pans are present, vegetative responses to ripping will almost always be obtained, but if finishing rains or soil moisture is limiting, yield responses may be curtailed.

Medium textured soils such as the Avon Valley loams, and heavier soils (salmon gum-gimlet) have not shown compaction pans, although soil strength may increase with depth. There has generally been no response to ripping, although the cultivation caused by the ripping operation sometimes has a fallowing effect as it kills the pasture. This is not a ripping response as it is also obtained (at a fraction of the cost) with a shallow cultivation.

Duplex soils of sand over clay and sand over gravel have traffic pans if the sand is deep enough. Generally sand over clay soils will not respond to ripping unless the clay is deeper than 25 cm. Sand over gravel soils have responded to ripping if the gravel is in a sandy matrix and does not restrict root growth completely.

Yellow loamy sands with highly acidic subsoils (wodgil) commonly form compaction pans at 15 to 20cm. However, wheat crops seldom respond to deep ripping because root growth (and therefore nutrient and water uptake by the plant) is restricted by the subsoil acidity.

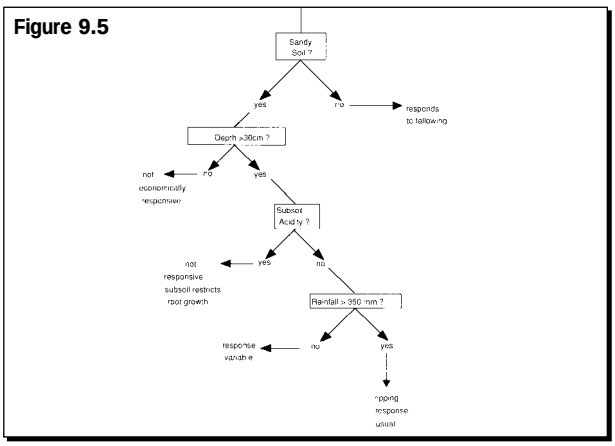
Even on suitable soils, responses to ripping have been

■ DEEP TILLAGE *(continued)*

least reliable in areas with less than 350 mm annual rainfall. This is probably because the soil may not become moist deep down in the soil profile, and ripped or not, the roots have access to all the water available in the profile.

These factors are summarized in Figure 9.5.

Figure 9.5



Factors to consider in deciding whether to deep rip.

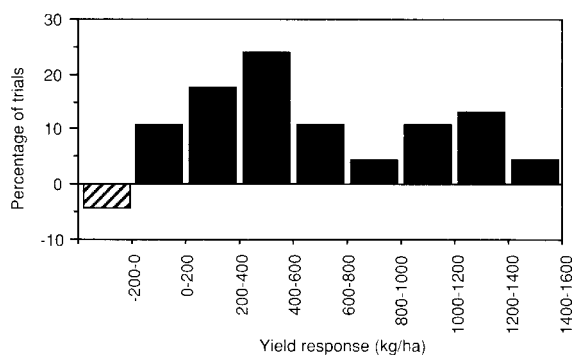
Yield responses to deep ripping

On suitable deep sandy soils there have been consistent and very large responses to deep ripping.

Figure 9.6 shows the variability over 46 experiments conducted between 1981 and 1989 on yellow loamy sands from Tammin to Yuna. Of the 46 experiments, yield has been decreased in only two after deep ripping.

The most common response to ripping has been a yield increase of 400 to 600 kg/ha (median response 540 kg/ha) with an average response in the year of ripping of 653 kg/ha when compared with a normal cultivation. Ripping increased the average yield from 1.77 t/ha to 2.42 t/ha.

Figure 9.6



Yield response to deep ripping on yellow loamy sands.

Residual value of deep ripping

The response to deep ripping can last for a few years which helps spread the cost. The advantage from ripping declines in time due to:

- Recompaction by traffic;
- Natural soil settling; and
- The greater removal of nutrients and water by the previous year's higher yielding crop.

In an experiment at Wongan Hills, yield responses to a single ripping have been obtained in the eighth crop in a wheat:lupin rotation. Over the eight years the total extra wheat yield has been 2.24 t/ha from the single ripping, with little response from the lupins.

The lower (often zero) response by lupins to ripping is because the lupin taproot is less restricted than wheat roots in penetrating traffic pans; and lupins, being leguminous, produce their own nitrogen.

The popular belief is that wheat responses last for over three years from a single ripping. In a wheat:lupin rotation, ripping every second wheat year is a compromise between optimizing yield and being able to handle the seasonal ripping programme in the limited time available.

Additional benefits of deep ripping

Soils responsive to deep ripping may be groundwater recharge areas.

Apart from the productivity gains using deep tillage, the higher yielding wheat crops will use substantially more water, and will reduce the leaching of nitrate through deeper rooting and greater nitrogen uptake.

Because the soils responsive to deep tillage are coarse textured, they are likely to groundwater recharge areas, and susceptible to soil acidification (due in part to nitrate leaching).

Deep tillage may therefore form an important part of a sustainable farming system for the sandplain.

Deep ripping has also been shown to reduce the incidence of rhizoctonia bare patch resulting in increased wheat yield (Jarvis and Brennan 1986).

When to deep rip

Deep ripping is slow and costly. For maximum yield response, the depth of working must be below the traffic pan and this may mean penetration to at least 30cm. Moist soil throughout the ripping depth is necessary to reduce power requirement and point wear and to obtain efficient softening.

Soil moisture availability is the main limiting factor in fitting deep ripping into the farming system in Western Australia. Pasture can be ripped in July, often with little effect on the pasture. However, in the areas of Western Australia where ripping has been adopted the fastest, responsive soils are usually cropped continuously with wheat and lupin rotations. The time available for ripping is following summer rains, or at the break of the season before sowing wheat. Ripping at the break conflicts with lupin seeding, or with early sowing of wheat. Delaying wheat planting can reduce yields, however, this must be weighed against potential yield advantages from ripping, including its residual value.

■ DEEP TILLAGE *(continued)*

Ripping immediately after seeding avoids machine flotation and depth of seeding problems associated with seeding on soft, ripped ground (Table 9.6). In areas which show reliable responses to deep ripping, more than 25% of the area ripped each year was carried out post-seeding in 1988 (Jarvis 1991) and this practice has increased since then.

Table 9.6 – Effect of deep ripping before and after seeding on wheat yield

Time of deep ripping	Wheat yield (t/ha)
6 days before seeding	2.18
Immediately after seeding	2.32
3 days after seeding	2.23
7 days after seeding	2.03
14 days after seeding	1.82
No rip, direct drilled	0.75

The whole operation must be carefully managed, as research in 1986 showed that plant number and yield can be reduced where tractor wheel slip was high when ripping seven days after seeding. Ripping three days after seeding was not a problem, however, an increase in seeding rate would be worthwhile insurance. The yields from ripping 7 and 14 days after seeding are higher than would be obtained for a paddock operation as the yields were obtained from the crop area between the wheels of the tractor doing the ripping – where wheat establishment was only reduced by 15%. Where wheel slip had occurred, establishment was reduced by 70%. Establishment was not affected at the other times of ripping.

Ripping carried out (when soil moisture was 'adequate') from July/August of the preceding year, on summer rains, or pre- or post-seeding have produced similar wheat yield responses. Ripping in dry conditions was less effective and the cost if the operation was prohibitive because of fuel use, reduced speed and point wear.

Speed of ripping

Available tractor power and traction control the speed of ripping. In the operating range of speeds there was little effect of speed on the amelioration of compaction and the resulting effect on yield. Speed was relatively unimportant compared with depth or tine spacing in its effect on fuel use. Farmers rip at an average speed of 7.3 km/h (a range of 4.0 to 12.9).

Fuel usage

Farmer's estimates varied considerably because of available power, size of implement, and the variation of soil types, compaction strengths and soil moisture conditions and averaged 8.1 L/ha (4.6 to 13.0 range).

Farmer adoption of deep ripping

The cost of a specialized machine, availability of labour, the need for a spare powerful tractor and the variability of grain yield responses has inhibited the adoption of deep ripping.

However, nearly all farmers who have bought a ripper continue to rip when seasonal conditions allow. In most cases, the aim is to rip every second wheat crop in a wheat/lupin rotation, in other words, one quarter of their cropped area each year.

Further attention to responses to deep ripping in the south coastal cropping zones will be essential, in particular, within high yielding package strategies. The previous history of research on the south coast showed reduced production from crops established with zero tillage because of the lack of early vigour as well as increased rhizoctonia bare patch.

Some machines can now deep rip and seed in one pass which reduces the requirement for an additional tractor but can slow seeding.

Research results, and experience by farmers, indicate a much larger potential for adoption of deep ripping as a standard farm practice in Western Australia.

Further reading

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Jarvis R.J. (1992). Amelioration of soil compaction with deep ripping. Proceedings of the National Workshop on Subsoil Constraints to Root Growth and High Soil Water and Nutrient Use by Plants, Tanunda, South Australia, August 30- September 2.

McFarlane, D.J. (1984). Soil conservation research in NSW and its significance to research on water erosion in Western Australia. Western Australian Dept. Agriculture, Division of Resource Management Technical Report 29.

Jarvis, R.J. and Brennan, R.F. (1986). Timing and intensity of surface cultivation and depth of cultivation affect rhizoctonia patch and wheat yield. Aust. J. Exp. Agric. 26:703-8.

MANAGING WATER REPELLENT SOILS

Paul Blackwell

Up to five million hectares of Western Australia is affected or has the potential to be affected by water repellency or non-wetting. These are mainly sandy soils with less than 5% clay content in the West Midlands, Swan coastal plain and the south coast sandplain. Large areas of South Australia, on the Eyre Peninsula and in the south east, are affected as well as parts of the Victorian mallee.

Water repellent behaviour in soil is caused by dry coatings of hydrophobic (that is, water hating) material on soil particles or aggregates, as well as hydrophobic organic matter, such as fungal strands and particles of decomposing plant material. Methods of assessing repellency are explained in Farmnote No. 110/96 'Assessing water repellency'.

Symptoms of repellency problems in pastures

Patchy emergence early in the autumn typifies pastures on water repellent soils. Light rains accumulate in hollows and hoof prints and wet the soil sufficiently for plants to survive for a few weeks. The pasture has patches of plants on wetted areas with dry, bare ground in between.

Subterranean clover is at a competitive disadvantage to aerial seeding plants. Its runners do not preferentially place the seeds in the hollows, and seeds placed just below the soil surface may or may not be wet by light rains. When they do germinate, the roots may find only dry soil underneath the seed, so the seedling dies. This can lead to a decline in the productivity of clover pastures.

The pasture contains younger and older plants, which results in difficulties with some herbicides, which are best applied at specific growth stages.

Insects (for example, redlegged earth mite) are able to multiply quickly because of the early germination and survival of plants which are good hosts (for example, capeweed).

Symptoms of repellency problems in crops

Repellent soils require more rain at the break of the season before seeding than non-repellent soils. This delay in seeding can significantly reduce the yield potential of the crop.

Crops that are sown before the soil is evenly wet will result in patchy germination. Controlling the depth of cultivation and sowing equipment is difficult when moving alternately from wet to dry soil.

The wind erosion risk is increased by the forced delay in sowing as well as by dry soil patches and poor cover.

Fertiliser placed in the hollows could be subject to increased leaching, while fertiliser in dry soil is less available.

Incorporated herbicides (for example, trifluralin) are not always active in dry soils. Surface applied herbicides (for example, simazine) can be washed into hollows and damage crop plants, while weeds germinate on the rises.

Heavy rain in summer or autumn can result in significant runoff and erosion on repellent soils on sloping sites. Rills and gullies have been observed on soils, which would have negligible runoff if they were not repellent. Water erosion can occur on both crop and pasture paddocks.

Advantages of water repellency

Not all the consequences of water repellency are necessarily unfavourable and some native plants may induce water repellence to give them a competitive advantage in a harsh environment. Water repellence can reduce moisture loss through evaporation by the 'dry mulch' effect of the repellent surface layers. It can also increase the amount of subsoil moisture by diversion flow from the surface through preferential pathways beneath surface hollows and along plant roots. However, there are also possible disadvantages of diversion flow, due to the faster transport of nutrients and toxins into water supplies.

Causes of water repellency

There are two requirements for a soil to develop water repellence; firstly, the accumulation of a sufficient quantity of hydrophobic organic matter and secondly, a susceptible soil.

Hydrophobic organic matter

Particles of organic matter seem to act as a highly hydrophobic soil component and as a carrier and reservoir of waxes. These waxes can diffuse out under heating and cooling cycles (for example, over summer) which redistribute the hydrophobic materials. This makes the adjacent sand grains hydrophobic. A number of different organic compounds have been identified. The waxy substances consist of long chain hydrocarbons, fatty acids and alkanes (paraffin-like compounds).

There is some evidence from long-term experiments in the West Midlands and on the south coast of Western Australia that continuous cereal cropping may reduce repellence, providing the soils are not severely repellent. However, there are many agronomic disadvantages of continuous cereal cropping.

Blue lupins, *Lupinus consentinii*, definitely increase the severity of water repellence. A sandplain paddock growing blue lupins continuously for about five years will develop moderate to severe repellence.

Sheep camps tend to be more water repellent because of the accumulation of organic matter. The waxy substances in plants are not effectively broken down by their passage through the sheep.

In native vegetation there is a strong link between

■ MANAGING WATER REPELLENT SOILS *(continued)*

particular species [for example, *Eucalyptus astringens* (brown mallet), *E. patens* (blackbutt) and *Banksia speciosa* (showy banksia)] and the induction of water repellence.

Soil susceptibility

The soil property which is closely linked to susceptibility to water repellence is the surface area. For instance, coarse sands can be more repellent than fine sands when the same amount of organic matter is added. Coarse sand has a lower surface area than the same weight of fine sand. Clay has a very much larger surface area than sand, because it consists of much finer particles. Thus soils with greater than about 5% clay content rarely exhibit repellency. Coarsely aggregated clays and soils with an abundant supply of hydrophobic material, such as beneath brown mallet hilltops, can be exceptions to this general rule.

Microbial activity breaks down dead plant material in a way that contributes to the development of water repellence in susceptible soils. It seems there is selective degradation of less hydrophobic waxes resulting in concentration of the more repellent polar waxes. Some micro-organisms can degrade the more stable hydrophobic waxes. Research continues for a biological solution to water repellence using similar principles to that of biological clean-up of crude oil spills.

Recent results encourage the use of moisture conservation, pH correction with ground limestone and the addition of small amounts of clay.

Solutions

Possible management solutions depend on the location, landscape and agricultural enterprise.

Claying

Claying is currently the best long-term solution to correct the problem for better cropping and pastures. Suitable top-dressed or delved clay can cover the repellent soil particle surfaces and improve soil water retention and nutrition, but is relatively expensive initially. See Farmnote No. 37/94 'Claying water repellent soils' for more details.

Furrow sowing and zero-till

The easiest solution for better cropping on these soils is to employ furrows. The retention of thick surface mulch in a zero-till regime without grazing can also reduce opportunities for soil drying and minimise repellency. Further technical details on furrow sowing and zero till are provided in Farmnote No. 111/96 'Furrow sowing for improved crops and pastures on water repellent soils' and Bulletin 4333 'Furrow sowing on water repellent soils'.

Permanent pastures

Permanent pastures of blue lupins, serradella or lucerne are possible options, if care is taken with the method of establishment. Fodder shrubs such as tagasaste often prosper on water repellent soils, as do trees such as pines.

Lime and gypsum

Lime and gypsum are often mentioned as possible solutions, but have been very disappointing in most experiments in Western Australia.

Dilution

Repellent soil layers can be diluted with deeper, non-repellent soil to reduce the problem, but this can lead to a large wind erosion risk and is not a long-term solution.

Further reading

Bulletin 4333 'Furrow sowing on water repellent soils' (Agdex 510).

Farmnote 37/94 'Claying water repellent soils' (Agdex 514).

Farmnote No. 110/96 'Assessing water repellence' (Agdex 511).

Farmnote No. 111/96 'Furrow sowing for improved crops and pastures on water repellent soils' (Agdex 511).

■ CLAYING WATER REPELLENT SOILS

Dan Carter and Rob Hetherington,
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Summary

How claying works; results of claying non-wetting soils; types of clay; methods and costs of claying.

Farmers in Australia are benefiting from adding clay to water repellent soils, 'claying', by improving water entry and uniform soil moisture.

South Australian farmers have been adding clay at up to 200 t/ha to the topsoil of sand dunes, with remarkable productive results from these soils. The claying has been effective even 20 years after the original applications.

Following the South Australian clay success story, Agriculture Western Australia has been developing the best techniques for claying our water repellent soils.

Principles of claying soils

Sand grains in susceptible soils are covered with organic materials that are non-wetting. Clay can be added to coat the sand grains and organic materials so a new wetting surface is developed.

Clays that spontaneously slake and disperse are the ones to use because rain breaks them down quickly and they disperse on to the non-wetting surfaces.

This leads to the soil wetting up uniformly, improving the germination of both crops and pastures. Crop establishment is easier, because competitive weeds are more controllable due to their uniform germination. Herbicides and nutrients are also far more effective when the soil is evenly wet.

Results of claying non-wetting soils

In Western Australia, the increases in productivity after adding clay have been encouraging. In the south coast region, barley yields on water repellent soils were increased by an average of 70% each year after adding clay. Yields in trial plots improved from 1.7 t/ha on water repellent soil to 3.4 t/ha on clay treated soil in the second year. Farmer yields have gone from 1.2 to 2.8 t/ha.

Benefits have been shown in the west Midlands and northern agricultural regions in the second year after application. The yields of lupins and wheat improved from about 1 to 2 t/ha. This is twice the yield of these crops on untreated soil in the west Midlands.

The improvement can be put down to several things:

- better weed control in the pre-sowing phase; a uniform germination makes them easier to spray,
- more even water penetration of the soil surface,
- retention of soil water in the clayed layer,
- retention of plant nutrients in the root zone, particularly potassium, and
- earlier planting dates, as less rain is needed to wet the seedbed.

Adding clay to permanent pastures also increases production and has a better plant composition. The effects of the clay encourage clovers and serradella at the expense of capeweed. Clay can also help to slow soil acidification and prevent water and wind erosion. The clayed soil has been very resistant to wind erosion, particularly in areas without ground cover.

Types of clays

Kaolinite, or white pipe clay, is the best of the clays; it is dominant in the subsoils in Western Australia, particularly in southern regions and can be yellow red or green depending on the other minerals present.

The most suitable clays are the ones that disperse in water forming a cloud of clay – they do this naturally when incorporated into the topsoil (see Farmnote No. 57/90 'Identifying gypsum responsive soils' -Agdex 514).

The dispersion speeds up the process of coating the sand grains and non-wetting organic matter. Very little mechanical incorporation is needed.

Non-dispersive clays have worked in laboratory experiments but they need far more mixing and may be uneconomic and slow to take effect. These clays suit cropping soils only, where cultivations mix the clay into the surface.

About 3% clay is needed in the top 50 mm of soil. However, because most subsoil clays are mixtures of sand and clay particles, with between 20 and 50% actual clay, the application rate recommended is 100 t/ha. This has been successful in trials.

Methods of claying

There are two ways to get clay on to the soil surface – spreading and clay lifting.

Spreading and mechanical incorporation

Some farmers in South Australia dig dams using road scrapers with elevators and "Carry Graders". The clay spoils are then spread onto the paddock. These farmers treat the problem areas such as sand dunes first. The clay is dumped in parallel rows and incorporated into the soil by scarifying or "smudging" with railway irons at angles to the original rows. The farmers do about 50 ha to 100 ha at a time.

The "Claymate", a machine developed in South Australia, rips and scrapes up clay and spreads it evenly on the paddock, without the need to cross scarify. Road scrapers can be used to give a continuous blanket of clay at 100 t/ha without cross scarifying. High driver skill is required to overlap the rows at the correct application rate.

Spreading is the only method possible if the clay is either not available on site or is too deep for the next method.

■ CLAYING WATER REPELLENT SOILS *(continued)*

Clay lifting or "delving"

With duplex soils, suitable clay is often within 600 mm of the water repellent topsoil. A clay lifting technique, clay delving, can pull up the required quantity of clay without inverting the whole soil profile.

It was first tried in Great Britain on acidic soils lying over alkaline marl. The technique is to pull a flat-faced delving tine through the top of the clay layer. The clay runs up the face of the tine and is deposited on the soil surface. The depth of penetration into the clay subsoil controls the amount of clay pulled up. Under Western Australian conditions, 100 to 130 t/ha have been well within its capability.

The drawback at the moment is that with domed-clay soils the clods sizes are too big and need to be broken down with rolling and cultivation. If a dispersible clay is lifted, the clods will disintegrate and disperse naturally when it rains during the winter months. Sheep trampling will also help to break down and incorporate the clay.

The width of the test delving tine is tapered from 150 mm at the bottom to 100 mm at the top where it emerges from the soil surface. In trials, this single tine was pulled through the soil at 2 m spacings to lift the clay. The tine was on a three point linkage behind a 32 kW tractor travelling at 5 km/h. It pulled clay up from a depth of between 200 and 300 mm.

Future thoughts are to halve the width of the delving tine face, so that the clods pulled up are smaller, and to have the tine rip lines 1 m apart. The tine would also be longer to reach clays 600 mm deep. Beyond this, tractor draw power may limit the ability of the technique. Longer, narrower tines have lifted clay from 600 mm at Esperance.

The method may cause problems in the subsoil because the soil in the rip line can disperse during rainfall, resulting in gross waterlogging. Gypsum may be needed to stabilise the disturbed soil in the rip lines.

Costs of claying

Costs vary on claying in Western Australia dependent on the type of machines used. Quotes of about $150-200 per ha have been obtained for digging, carting and spreading clay. The delving tine method may be similar in cost to deep ripping, which is currently between $30 and $45 per ha.

The yield increases obtained by overcoming the water repellency would pay for the treatments in two years. However, it may be possible to integrate the costs of claying into other farm activities. For example, there is considerable interest in preventing waterlogging on some shallow duplex soils by digging drains with road scrapers. The clay from these drains could be disposed of on the deeper sandy rises where water repellency is a problem.

The benefits to both areas would pay very quickly, especially by creating more uniform land management units across the whole paddock. The benefits of claying last about 30 years.

Further reading

Farmnote no. 57/90 'Identifying gypsum responsive soils' (Agdex 514).

Journal of Agriculture (1993). 'Improving sustainable production from water repellent sands'. Vol. 34, No. 4.

MACHINERY FOR STUBBLE RETENTION AND WIND EROSION CONTROL

Paul A Findlater and Glen P Riethmuller

To control wind erosion about 50% of the surface should be covered with prostrate stubbles. If plant residues are detached or easily blown by the wind, for example, pea stubbles, then much higher levels are required for wind erosion control. If the stubbles are standing then as little as 20 to 30% cover is required to reduce the risk of erosion, because the standing stalks greatly reduce the wind speed at the soil surface.

No-till sowing, if used correctly, will minimise wind erosion. It aims to maintain ground cover and reduce soil disturbance, so is well suited to controlling wind erosion. However, some no-till seeders may push the stubble flush with the soil surface; this will reduce its effectiveness against wind erosion.

Some no-till seeders bury as little as 10% of the stubble and leave many of the stalks standing, providing even greater protection against wind erosion. Under the conditions of a trial at Wellstead in 1993, no-till tine seeders tended to bury more stubble than no-till disc seeders (Table 9.7). However, some no-till disc seeders will bury significant proportions of dry lupin stubbles in sandy soils.

In relation to controlling wind erosion, little advantage is gained from using a no-till seeder if, either as a result of over-grazing or burning, the pasture or stubble residue is almost non existent. After seeding, the surface will still remain loose and exposed – particularly some grey sands and soils which do not form a crust after rain. The cost per drill row of no-till disc seeders may be greater than conventional seeders, but the advantages must be weighed against the cost of erosion.

The level of stubble reduction of a seeder depends on a number of factors including the number of passes, machine type, stubble type and condition, and soil type and moisture. The commonly used full-cut tine, offset disc or culti-trash seeders bury as much as 80% of the lupin stubble in the first pass. Such tillage can reduce stubbles from a two tonne per hectare lupin crop with 30 to 40% cover to less than 10%, even with direct drilling – well below levels required for adequate wind erosion protection.

An extra tillage pass will not significantly affect the percentage cover, because the stubbles have already been mixed with the top soil. Additional workings merely turn the soil over, bringing some of the already-buried stubble to the surface, and burying more. Rotary harrows had little effect on maintaining ground cover, however it has been observed on heavy soils that rotary harrows are more effective at leaving wheat stubble on the surface when the soil is dry or moist but not wet and the stubble is dry.

Table 9.8 shows typical cereal stubble levels remaining after seeding with a range of machines. The amount of stubble remaining on the surface will vary with machine and stubble type and location. They contrast with those for lupin stubbles in the northern agricultural area of Western Australia; the percentage of stubble buried in the northern agricultural area is higher. In many cases the traditional seeders, even with direct drilling, may not leave enough cover for adequate protection against wind erosion. Each grower should make an independent judgement about the performance of the particular seeders used, and ensure sufficient stubble is left on the surface to minimise the risk of erosion.

Table 9.7 – Percentage reduction of ground cover in a cereal stubble for various no-till machines in one trial at Wellstead in 1993

Treatment	Total stubble (% cover)			Standing stubble (stalks/m^2)		
	Before	After	Buried	Before	After	% reduction
Tined seeders						
No-till knife points 180 mm row spacing	81	26	55	8	1	89
No-till Conserva-Pak® 225 mm row spacing	76	30	46	14	5	64
Narrow points 360 mm row spacing	81	35	46	11	1	88
Disced seeders						
Cross-slot®	83	67	16	8	2	76
Biomax®	80	76	4	6	5	23
Germinator®						
Great Plains®	77	80	-3	9	5	46
Great Plains® + wavy coulters	75	72	3	12	5	61
Morris® double disc	83	79	4	9	5	45

■ MACHINERY FOR STUBBLE RETENTION AND WIND EROSION CONTROL *(continued)*

Table 9.8 – Surface reduction of cereal stubble by various tillage machines.

Implement	Reduction of cover per working (%)
One-way plough	30 – 85
Offset disc	50
Tine combine	50 – 60
Culti-trash	75 – 80
Chisel plough (sweeps)	15
No-till disc	0 – 20

Choice of a seeder

A decision for farmers considering adopting no-tillage practices concerns the choice of machinery as stubble handling at seeding is a major consideration.

Disc machines handle stubble fairly well and are ideally suited to light soils that are prone to wind erosion. However, they are not as versatile as tined machines which can be easily reconfigured for a variety of soil and crop conditions. Chemicals that need to be incorporated also present a difficult challenge with this type of machine.

Tine machines are less able to cope with stubble than disc seeders. Successful use of these seeders in a stubble retention system requires preparation of stubble at harvest, which may cost more in time and wear on the header. However, they have the ability to use points of different shape and size to match a range of requirements for soil disturbance and fertiliser placement. Wider row spacings improve the stubble handling ability but wheat yields may be reduced.

There is a range of new machinery or conversions for existing machinery available for farmers contemplating retaining their stubble. Farmers can choose the most cost effective machine for their particular environment, soil type, cropping area and budget.

Seeding into poorly managed wheat stubble can be a problem especially if heavy sheep grazing is not an option. Seeders have been developed that handle stubble but even these will not perform where the stubble has been managed poorly. Good stubble management begins at harvest, which then avoids problems at seeding. Some options are described below, as well as ways of handling stubble before or at seeding time.

Disc seeders

The first triple disc seeders consisted of a leading coulter set in line with the direction of travel. This opened the soil and a paired or double disc followed which cut a groove in which the seed was placed. These machines were not particularly successful. One of the biggest problems was that in soils with 10% or more clay (that is, loams and clay loams), the slot was left open and seed was either droughted or flooded. Emergence and crop yields were unreliable and often poor.

Later triple disc machines have a furrow-following press wheel, which controls the depth of the double disc and closes the furrow by placing soil over the seed.

Some recent triple disc seeders used in Western Australia have replaced the plain leading coulter with a wavy disc. This is self-sharpening and cuts through stubble residue as well as disturbing some soil in a narrow slot. The slot of disturbed soil leads to better seed-to-soil contact and has the potential to control or reduce the incidence of Rhizoctonia bare patch disease (Farmnote No. 68/96 Crop disease and no-tillage farming).

However, in particularly loose sandy soils or soft wet soil these coulters may be unable to cut stubble and instead push it into the soil in a folded form ("hair pinning"). Stubble pressed into the seed furrow may cause poor emergence from preventing adequate seed-to-soil contact and drying of the seed zone as well as toxins from the stubble reducing emergence.

Modern triple disc seeders are more solidly constructed than the original triple disc machines and penetration on firmer soils is improved. However, even though using coulters with deeper waves can increase the amount of soil disturbed, the amount of disturbed soil may still be less than adequate. For example, some soils may need more disturbance than others or fertiliser may be better placed below the seed (Farmnote No. 71/96 'Banding fertilisers in no-tillage farming').

One innovation to increase the amount of soil disturbance is an angled coulter. This has been used successfully to place the fertiliser below the seed and thus avoid or minimise adverse fertiliser toxicity effects, particularly in no-tillage seedbeds.

These machines are quite expensive per unit width but offsetting this cost is the advantage they have in handling high stubble levels.

Chaff spreaders on the headers are essential to reduce the depth of stubble and spread any weed seeds evenly.

Disc seeders may have a problem of clay soil sticking to the discs but if the sowing time can be adjusted to avoid very wet clay there should be few problems.

In stubble retention systems, discs generally provide timely untroubled seeding, which improves the chances of obtaining higher yields and profits.

Tine Seeders

For tined seeding machines to operate effectively in stubble, management of the stubble at harvest is essential.

Six-bar combine seeders and modern multi-bar air seeders have been designed to handle higher levels of stubble. The tine spacing on each bar is greater; allowing appropriately managed stubble to flow between the tines.

Stubble length rule of thumb

A rule of thumb to allow tined seeders to operate efficiently in stubble is as follows:

■ Reduce the length of all standing and cut stubble to

MACHINERY FOR STUBBLE RETENTION AND WIND EROSION CONTROL *(continued)*

half the smallest clearance distance in the seeder and all the cut stubble and chaff should be spread evenly. This distance is between the nearest tines in any direction and can be much less if large seed boots or press wheels are attached to the tines. This clearance distance also includes between the underframe and the soil surface with the seeder in the soil at working depth.

The traditional tined seeders were for primary or secondary tillage with seeding being done only after some form of tillage. As direct drilling and then no-tillage crop establishment in retained stubble were adopted, the need for a primary tillage machine was reduced and seeders had to be more robust. The tine tension or tine break-out pressure generally increased to ensure the tines penetrated firmer, undisturbed soil. Around 100 kilograms tine break-out force and higher is now generally required for one-pass no-till sowing, particularly if some disturbance below the seed is required.

The next problem faced by tined seeding machines was the need to handle potentially large quantities of stubble. Some of the methods used to cope with stubble are outlined below.

- Increase the clearance between tines by using wider row spacing, wider bar spacing or more bars on the seeder and higher underframe clearance tines, such as chisel plough tines.
- Cut or move the stubble away from in front of the tine.
- Use a rotary harrow to spread out stubble lumps and level the seed bed.

Burning options

The use of 'hot' burns (a running fire in hot weather) to manage stubble in the Western Australian wheatbelt is not generally advisable. All the stubble is burnt, allowing for trouble free seeding, but the soil is left very vulnerable to wind and water erosion. However, if herbicide resistant weeds are a problem it may be a part of a management plan to reduce the weed numbers.

'Cold' burns (partial burning of the stubble in cooler weather) are commonly used to reduce the level of stubble in a paddock before seeding. Cold burns can take a number of forms including fire harrowing strips in the paddock or burning the header trail only in light stubble levels. This is an effective way of reducing stubble levels, but it could easily get out of hand and become a 'hot' burn. Burning canola windrows left unspread by the header may help reduce the number of herbicide resistant weeds, as the trail burns very hot.

Raking with a stubble rake and burning the windows is effective in reducing the level of stubble on the paddock, but if not carefully controlled, could also become a hot burn. It is generally best to burn the windows at night and have all the fire put out before morning as winds generally pick up and could burn the whole paddock.

Burning operations to manage stubble must be performed as close to seeding as possible to reduce erosion risks. However, stubble management at harvest may effectively allow seeding to proceed earlier without the need for burning.

Stubble management at harvest

The first option is to reduce the height of the standing stubble. Mounting a second cutter bar just below and behind the header front can do this. The straw that passes below the header front is cut in half by this second cutter bar. Reducing the straw length after harvest with a mower or slasher is not always successful due to the long stubble pushed over in the header wheel tracks not being cut. Slashing can also be a fire risk, particularly if stones are present.

A second cutter bar removes the need to take large quantities of straw through the header, making it ideal for headers that do not have the capacity needed for the option of cutting low, and chopping and spreading the straw and chaff. However, availability, reliability and header warranty issues are a problem.

Harvesting at an angle to the seeding direction can alter the distribution of straw that confronts the seeder the following season. This means that a smaller amount of uncut straw, compacted by the header wheels, enters the seeder at any one place and may allow a better chance of getting through the stubble.

Another way to leave short standing stubble is to cut low and then chop and spread the straw and chaff with the header. The ability of the header to do this depends on its power and capacity. The extra bulk of material that must pass through the header and the extra attachments needed limit this option to larger headers with open fronts. However, if only those paddocks that are to be sown into stubble are treated this way it still may be the best option. Also weed seeds may be collected if a catcher bin is attached.

Headers use two types of threshing system, rotary and conventional. Rotary headers tend to break up the straw during threshing. The straw passes around the threshing drum more than conventional headers do before it is discharged. An attachment to chop up the straw further on a rotary header may not be necessary in light crops. Straw and chaff spreaders are necessary to spread it evenly across the width of the cut.

Headers with a conventional threshing system do not break up the straw during threshing so chopping and spreading attachments are necessary.

Another option is to leave the straw in the header trail and then baling the straw. This option may only be suitable where a market for the straw is available but it is a good option where very large amounts of stubble are present – particularly if canola is to be sown into the stubble.

Straw chopping attachments

Straw choppers consist of a series of blades, mounted

MACHINERY FOR STUBBLE RETENTION AND WIND EROSION CONTROL *(continued)*

on a horizontal rotating shaft. The moving blades interact with a static series of knives to chop the straw into 50 to 100 mm lengths and spread it behind the machine.

Straw choppers are also mounted under the rear hood of the header and may be swung out of the way for service access or to lay the straw in a window if desired. Most straw choppers do not spread chaff; an extra chaff spreading attachment is required for this.

Straw choppers have high power requirements – up to 22 kW (30 hp). If it is attached to a header whose prime mover lacks sufficient extra power to drive them, substantial reductions in capacity may be expected. Reductions of up to 14 per cent have been measured. Fire hazard potential may be increased when using these attachments due to the extra quantity of fines around the header.

Chaff spreaders

Chaff spreaders usually consist of a pair of counter-rotating discs with cleats mounted under the sieves to spread the chaff. Most header manufacturers have these options for their machines. There are also a number of farmer-made spreaders that are easily constructed.

They use very little power and are necessary on all types of headers to spread the chaff. If the chaff is left in the header trail, it can concentrate the weed seeds and the dense chaff makes chemical weed control more difficult.

Summary

- To control wind erosion about 50 % of the surface should be covered with prostrate stubbles.
- If the stubbles are standing then as little as 20 to 30% cover is required to reduce the risk of erosion.
- Some no-till seeders bury as little as 10% of the stubble and leave many of the stalks standing, providing even greater protection against wind erosion.
- There are a number of seeding machines available that are capable of handling stubble. Disc machines handle stubble fairly well and are ideally suited to light soils that are prone to wind erosion. However, they are not as versatile as tined machines which can be easily reconfigured for a variety of soil and crop conditions. These machines will only function effectively if the stubble has been well managed at harvest.
- Burning stubble options are not generally recommended. However, carefully controlled cold burns or raking and burning are accepted means of reducing the stubble level. Burning header trails can also reduce the weed seed bank especially with canola header trails. Stubble management at harvest is the preferred option.
- Baling the straw is very useful if a market is available.
- Harvesting at an angle to the normal seeding direction may increase the stubble handling capacity of the seeder.
- A second cutter bar mounted below the header front to shorten the stubble successfully reduces stubble length.
- Cutting low and chopping and spreading the straw is generally restricted to headers with sufficient power and capacity.
- Rotary headers may not require straw choppers in light crops, but straw and chaff spreaders are still necessary.
- Conventional headers need a straw chopper to chop and spread the straw.
- Chaff spreaders are necessary on all types of headers for most conditions.

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NO-TILL

No-till is sowing a crop without prior cultivation and with very little soil disturbance at seeding. There are several terms that have evolved in Western Australian agriculture. The main useful tillage terms from most to least cultivation are:

- multiple tillage – replaces "conventional", as the convention has changed
- reduced – one pass prior to seeding with a full cut-out
- direct drilling – one pass seeding with a full-cut
- no-till – narrow/knife point seeding with less than full cut-out
- zero-till – disc seeding.

The term 'minimum tillage' is confusing as it can mean all of the above except multiple tillage and therefore it should be dropped.

Advantages

No-till with retained stubble has the potential to improve soil properties and increase sustainability. It can do this by lifting and modifying soil biological activity which gives excellent improvements in all aspects of soil fertility, being, physical, chemical and biological. These improvements lead to better farm management and sustainability. The main benefits of no-till, with appropriate agronomic management, include;

- almost no soil erosion through stubble retention and proper grazing management (especially in sandy soils)
- greater flexibility of farm operations through less time used at seeding and improved soil structure leading to better trafficability, more manageable soils and more timely seeding and other operations
- more precise seed placement with more even crop emergence, if seeded at correct moisture content
- more water harvested to grow the crop in dry areas
- often less in-crop weed emergence and safer use of trifluralin herbicide for weed control
- less labour, fuel and machinery costs per hectare
- consequently, better whole farm profitability and sustainability

No-till with stubble retention increases soil organic matter and biological activity.

Preparation

Profitable no-till cropping requires excellent crop agronomy. This is because "tillage covers a multitude of sins". Tillage has been used for thousands of years to kill pests (particularly weeds), reduce diseases and soften the soil for fast root growth and nutrient release. When adopting less tillage we need to manage these factors by other means. Rotation of crops is the principle tool that must be used for effective no-tilling.

Soil

All soils can be no-tilled however some compactible sandy soils (eg. Wongan loamy sands) may require occasional deep ripping, even in a no-till system. In sandy soils, no-till with stubble retention minimises wind erosion and where it leaves furrows, makes water harvesting easier in water repellent soils.

In clayey and loamy soils, no-till minimises run-off and erosion by water and improves soil structure. In dispersive loamy or clayey soils, no-till with stubble retention reduces splash erosion as rain drop impact is minimised. No-till is excellent for soils that slake and / or disperse and form surface seals or crusts or set hard on drying, as well as for cracking clay soils. These "Sunday soils" have a narrow-moisture-cultivation range and no-till allows early sowing and better trafficability when soil moisture is optimal.

Some soils with clay contents greater than a loamy sand are prone to slaking and / or dispersion. Ideally, heavy soils should be no-tilled and grazing should be eliminated when the soil is wet. Biological soil improvements are still not well understood, yet their impact is often obvious after three or more years. Retention of stubble has major benefits in increasing microbial activity, some of which suppresses rhizoctonia and 'take-all' when a new microbial species equilibrium is reached after a few years of no-tilling. Heavy stubble can also suppress crop growth particularly in the initial years of no-tilling.

Pre-season preparation

Good no-till starts years earlier with clean and diverse crop rotations. A good crop sequence reduces yield restrictions from pests and diseases and lessens the reliance on pesticides. By controlling weeds, which are hosts to diseases, problems with both weeds and diseases are reduced. However, the year before seeding good stubble management is also essential. The need to retain stubble, for soil and soil-life benefits, is shown by the results of a long-term experiment (Table 9.10) conducted at Merredin on a heavy (sandy clay loam) soil.

Table 9.10 – The effect of row spacing and stubble retention on soil properties and yield of wheat in 1995 on a heavy soil (after 9 years of the experiment).

	Stubble burnt	Stubble kept
Organic carbon (%)	1.01	1.11
PH ($CaCl_2$)	5.5	5.6
Water stable aggregates (%)	11	18
Bulk density (g/cc)	1.61	1.57
Protein (%)	1.61	1.57
Harvest yield (t/ha)	3.29	3.76

In order for tined machines to seed through stubble, the stubble will need managing. Many farmers have opted for wider row spacings to overcome this problem. Cutting the straw short and spreading it evenly improves residue

NO-TILL

flow. On sandy south coast soils, discs may have to be put in front of tines to improve flow. For this reason many farmers have opted for disc only machines in these environments. When the break to the season occurs, if weeds become well established much higher rates of knockdown herbicides are needed as no-till does not provide a second knock effect on the weeds as tillage does.

Seeders

Tines

A cheap and easy option for no-till beginners. Tine break-out needs to be at least 90-150 kg per tine and it can then be fitted with any of several knife or inverted T points. With combines, the boxes may need to be raised or a blower fitted to allow wide spaced tines (70cm between bars, 70cm under frame). Knife points with wider row spacings (>220 mm) can be an effective tool to fight herbicide resistance because it allows more effective use of trifluralin which is lightly covered by fine soil throw across the inter-row, provided no soil is thrown into the adjacent furrow. Wider rows also reduce residue handling problems, capital costs, cost of wearing parts, draft, tractor size and fuel use. However, cereal yields can sometimes be slightly reduced with wider rows (see Table 9.11) but the above benefits may out-weigh the negatives.

Discs

Disc seeders have the advantage that they can seed through a large amount of residue (with some pinning), give accurate seed placement (important in marginal moisture conditions), disturb very little soil (reducing weed emergence and conserving moisture), require less draft (with savings in tractor size and life and fuel costs) and will not rip rocks up. However, it will increase the risk of fertiliser toxicity (unless the seed and fertiliser are separated). A wavy or turbo disc placed before double disc seeders is mostly beneficial as most soils require disturbance below seed placement depth. However, care must be taken with discs to avoid smearing in wet clayey soils. New research on improved disc seeder designs, which can cultivate like knife points, but handle stubble better, suggests there are no yield penalties for replacing a deep working knife point with a deep working undercut disc. Capital and running costs of disc machines are no greater than 'high-tech' tine seeders.

Soil disturbance (3-10 cm) below the seed gives quick root growth and early vigour in sandy soils and can be achieved with discs or tines. In clayey soils, shallow working points reduce draft, give better depth control, fewer clods, more even establishment and improve the ability of crops to compete with weeds. Under-seed disturbance reduces rhizoctonia, which is a problem in some sandy soils. Point type does not seem to affect yields. Inverted-T points are not likely to increase yield over knife points in Western Australian soils and seeding conditions, as their action differs very little.

Rotary harrows improve soil cover over the seed and incorporate chemicals but also encourage more weeds to germinate. Press-wheels reduce seed depth variation, and on moist clayey soils, often assist slot closure. Press-wheels are useful on very sandy soils and on drying soils, especially where clods form, to assist with even seeding depth, improve seed-soil contact, and assist moisture flow through the soil to the seed, particularly on non-wetting soils.

Seeder Set-up

Care should be taken in setting up the seeder to ensure that seed depth is even across the width and between front and rear rows, and that seeds are adequately covered. The setting up should be done at the proposed operating speed. Soil type and moisture content variations will vary the soil throw, so performance should be checked in the paddock when conditions change.

Fertiliser management

Nitrogen

Much of the N used by non-legume crops comes from crop residues and soil organic matter as they break down in the soil. No-till reduces the rate of this breakdown. In the first few years of no-till, the amount of N released will be reduced. However, as organic matter builds up, the breakdown will come back into balance with the rate of

Table 9.11 – Wheat yield average for 1988, 89, 90, 91, 93, 95 (t/ha)

Row spacing (mm)	Stubble burnt	Stubble kept	Average	% of 180mm
90	2.29	2.33	2.31	101.3
180	2.23	2.33	2.28	100
270	2.21	2.20	2.20	96.5
360	2.10	2.17	2.14	93.7
Average	2.21	2.26		
% of average	97.7	100		

Source: Riethmuller GP, Agriculture Western Australia, Merredin.

NO-TILL

organic addition and the amount of N released will return to that of the old system. The build up of organic matter is likely to be greater and may take longer in heavier than in lighter soils, so more N should be used in those soils in the first few years of no-till.

It is advisable to apply some N at seeding as N availability is slow early in the season under no-till. Avoid too much urea (<15 kg N / ha & nil for Canola) or ammonium fertiliser with the seed or under the seed in warm, moist conditions, especially in alkaline soils, as volatilised ammonia is toxic to germinating seedlings.

Phosphorus

There is no change to phosphorus fertiliser rates.

Micronutrients

Little work has been done with the placement of micronutrient fertilisers with no-till. We do not know how increased soil biology might affect applied nutrients. Micronutrients are physically immobile in the soil and move very little (2-3 cm) from where they are placed with the P or NP fertilisers. Their plant availability may largely depend on them being mixed through the soil volume. Therefore, with no-till, the aim is to have as many micronutrient particles spread through the soil volume as possible. This may mean applying them at a lower than recommended rate through several seasons.

Seed fertiliser dressings may also increase the number of particle sites but low rates need to be used as seedling germination may be affected. In years where the low rates are used, tissue testing and foliar application may be needed. Another possibility is to mix micronutrients with compatible chemical sprays.

Weeds

Successful weeds are adapted to survive in our farming systems. Each new method of growing crops will encourage some weeds, while others that are unable to adapt to the change becoming less important. No-till is such a major change. Benefits of these changes need to be exploited, but weeds that are well adapted to the new system must be watched out for and managed. Mallow is one such weed. Perennial weeds can be expected to become more of a problem. Weed seeds that do not self plant and so remain on the soil surface are exposed to a more hostile environment. Numbers may deplete steadily.

Weed control within no-till systems is highly dependent on herbicides and their timing. As such, care is needed to manage the weeds so that total predictable control is achieved of all growing weeds before planting. Robust rates of the knockdown herbicides are required and where necessary several applications may be needed. Utilise the double knock effect of glyphosate followed by Spray.Seed®. Additives such as Goal® for mallows should be used where necessary.

The precision placement of the crop with no-tilling, while leaving weed seeds on the surface, also provides an excellent window for Spray.Seed® use as cereal crops are emerging after most weeds. If Diuron has been applied, do not use this method if the cereal seedlings have emerged. Severe crop damage can occur.

Trifluralin with knife point sowing has increased the effectiveness of this herbicide dramatically. However rotation of this herbicide group is essential to avoid resistance. Weeds around the world have developed resistance to trifluralin. Take care with post plant/pre emergent application of soil active herbicides such as diuron. Sufficient soil (> 20 mm depth) needs to cover the seed to protect it from these herbicides.

Keeping the weeds “off balance” by not having a regular short rotation of herbicide types and crops will reduce their success in farming systems. Increasing the variability of the farming system can include green manure crops, opportunity summer crops, lucerne pasture and phased pasture-crop rotations. Harvest weed seed management with narrow header trails that maybe either sprayed or burnt are tools which can be used. Likewise, croptopping should be considered in legumes. Yield reductions can occur with croptopping if the application is compromised by weather or timing or weed maturity.

Under a no-tillage farming system, if good rotations and weed management strategies are in place, a reduction in total weed numbers will occur. However, a different weed spectrum could emerge. Remember that the biggest influence on weed burdens is crop rotation, followed by herbicides and then tillage.

Diseases

No-tilled crops can grow slowly and be susceptible to seedling diseases as they are growing in firm soil where only small amounts of N are released. Again, diverse crop rotation is the key. Keeping a high legume component in the rotation also ensures better N availability. Retaining stubble increases crop exposure to diseases later in the season. This risk is minimised by crop diversity and using a high proportion of legumes that increase soil organisms that digest and recycle the stubble.

Rhizoctonia bare patch is one disease that is more common with no-tillage. However, experience in South Australia, Esperance and Canada is that retaining stubble without stock grazing causes the disease to abate after 3-6 years. Even with severe rhizoctonia in these first few years, which has occured on the south coast, the damage has been greatly reduced with knife points working at 8 cm deep.

Insects

No-tilled crops usually have slower early growth and are therefore more susceptible to early insect damage. Lucerne flea and red legged earth mite will often damage no-tilled crops. Addition of insecticides with the

NO-TILL

knockdown is sensible insurance against insects. Retaining stubble with no-till helps repel aphids but may attract other pests at seeding and in the swathed rows. False wireworm has become a problem with south coast canola crops, which seems to be more severe with disc zero-till seeding. Using Lorsban® at 750 mL/ha in southern Victoria, with a trifluralin application has given effective control.

NO-TILL

CHAPTER TEN

DISEASES

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■ LEAF DISEASE

Principles of management

Leaf diseases are a universal phenomenon in Western Australian wheat crops. Their occurrence, severity and impact vary across regions in response to management and seasonal conditions. Rapid disease build-up and even spread within crops are general features of the biology and life cycle of most leaf diseases which undergo several infection cycles in a season and are readily dispersed in air or wind blown rain splash.

Management requirements vary with disease risk and potential for damage. Cropping practices are under continual development and several of them, such as early sowing, optimal nutritional management and increased stubble retention, can result in increased disease pressures.

Most wheat leaf diseases only attack wheat. This narrow host range assists in disease management options but the capacity of many leaf diseases to develop quickly under favourable conditions means that combining strategies that reduce risk of losses is usually required for optimal management. Integrating leaf disease management options is the key to successfully minimising effects of leaf diseases of cereals.

Rotation

Common leaf diseases such as septoria blotches and yellow spot survive and spread from infected stubble residues. One of the many advantages of crop rotation is that infected stubble residues are separated from the current crop, thus reducing disease risk. Separation of crop from disease source occurs both in space and time.

Without rotation a second wheat crop is placed in close proximity to the diseased stubble from the previous crop. This guarantees that disease spread into the current crop is early and possibly severe unless stubble is removed (thoroughly burnt or ploughed in). For this reason crop rotation is an important facet of stubble retention systems.

In a 1:1 rotation, the next wheat phase of the rotation is established 18 months or more after the harvest of the previous wheat crop. This time period is important in allowing the breakdown of the infected stubble residues.

Even in 1:1 wheat-lupin rotations where stubble is retained only about 5% of wheat residue remains after the sowing of the return wheat crop. This remaining residue is less infective than fresh residues that have survived for just one summer. The overall effect of reduced quantity and infectivity of residues after rotation is that they induce little, if any, disease in most situations.

How disease originates

The fungi that cause leaf spot diseases such as septoria and yellow spot survive in stubble and become active in the autumn, producing spores as the season opens. Most of these spores are dispersed short distances so double-cropped wheat can be infected severely.

Rotated crops avoid severe early disease but still become infected because other spores, dispersed long distances, are able to infect crops far away. This type of infection is usually mild initially, but provides an infective base from which the disease can increase as the season progresses if conditions are suitable.

Rust fungi require green living hosts to survive. Spores of wheat rust diseases produced on oversummering host plants (mostly wheat) are also spread by wind to new wheat crops.

The earlier disease originates in a crop and the intensity of this early infection are important determinants of how severe the disease becomes as the crop grows.

Initial effects of early sowing on disease

While all wheat crops are subject to airborne spores from remote sources, early sown crops are exposed to infection before later sown crops, giving disease a head start.

In April and early May sown crops the initial infections develop in mild autumn conditions allowing the fungus to mature quicker than in later sown crops whose initial infections develop in the colder winter months.

Early sown crops have greater initial disease because they have been exposed to more infections than later sown crops and these infections have been able to advance further before the winter sets in.

Moderate to severe leaf disease in young wheat crops can reduce early growth, but leaf disease of wheat in a rotation, which included legumes or oilseeds, would not generally be severe enough to significantly affect early growth.

The importance of disease in the early stage is as a source of infection later in the season.

Crop development and re-infection

Until late stages of stem elongation each stem produces new leaves continuously. Although disease spreads onto the new leaves, low levels of disease do not have a significant direct effect on yield. Disease progresses up the plant gradually as spores produced on lower leaves spread the fungi to newer leaves.

Plants may appear to outgrow the disease after winter as stems elongate and leaves develop rapidly. At this time the rate of development of new tissue exceeds the rate of death from new infections. However, this is a transitory phase. Infection will continue to develop after the plant has stopped producing new leaves and the disease will be able to ‘catch up’. It is at this stage that most of the differences in disease development between early and later sown crops occur.

The top two or three leaves on the wheat stem are crucial for grain production. Once produced they must remain green for as long as possible to ensure the plant completes grain filling.

From the moment the upper leaves are unfurled they are exposed to infection. The third top leaf (the second

LEAF DISEASE *(continued)*

below the flag) is exposed and becomes infected before the second top leaf. The flag is the last to emerge and be exposed to infection.

In very early sown crops these leaves emerge in the late winter / early spring when conditions are highly favourable for infection. Showery weather encourages the production and dispersal of spores from lower diseased leaves up on to the healthy young leaves and mild humid conditions keep leaves wet for longer. Such conditions are ideal for allowing spores to infect.

The early infection of upper leaves of very early sown plants allows several cycles of sporulation and infection to be completed on the upper leaves. Disease becomes more severe with each cycle.

Crops sown later do not develop upper leaves until later in spring. Diminishing showery conditions reduce the risk of significant spore dispersal to upper leaves and warmer, drier conditions reduce the extent of infections. Infection is reduced to the extent that the flag and second leaf (the leaf below the flag) are only slightly affected.

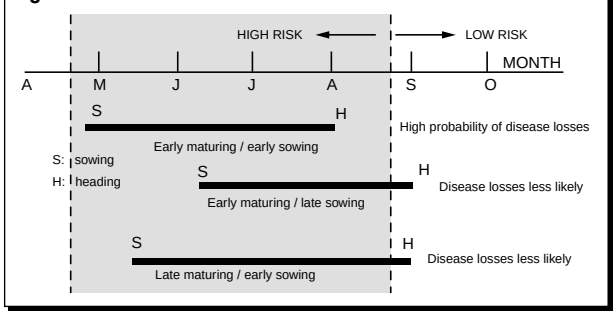
These infections, occurring later, are not as able to complete as many cycles of sporulation and re-infection because climatic conditions gradually become less favourable for disease spread.

Varietal maturity

Variety influences disease development and impact because of the different maturities and levels of disease resistance available. Early sowing has to be combined with a variety of appropriate maturity, and the degree to which sowing time can be advanced will be partly determined by the maturity of the variety chosen.

While early sowing will advance growth and increase disease risk, choosing a later maturing variety can offset the disease effects. The later maturing variety has a longer vegetative period before head emergence which delays flowering and grain filling to a time less favourable for disease development (see Figure 10.1).

Figure 10.1



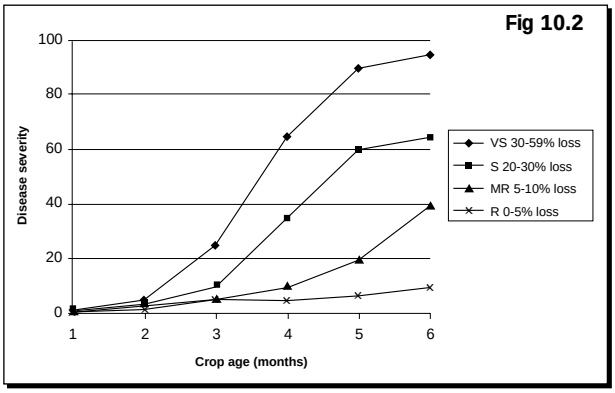
Sowing time and variety maturity affect disease risk.

Disease resistance

Disease resistance reduces or eliminates the effect of specific diseases, depending on the effectiveness of the resistance. Complete resistance, which is available for some diseases such as rusts, prevents disease occurrence. Partially resistant wheat will develop some disease but normally the rate of disease development will be slowed to the extent that disease effects on yield will be comparatively small.

Compared with susceptible varieties of similar maturities, the use of resistant or partially resistant wheats will significantly reduce the risk of yield losses from a disease. A variety may still be attacked by other leaf diseases for which resistance levels are low or absent.

Fig 10.2



Disease will develop earlier and more quickly on susceptible cultivars compared to resistant cultivars (VS = very susceptible, S = susceptible, MR = moderately resistant, R = resistant) and yield losses can range from 0-30% or more.

Seasonal influences

Disease activity is greatest during the spring period. This period most suits fungal diseases that grow best in warm, highly humid or moist conditions. Spore production is increased when leaves are moist and some spores, such as those of septoria diseases, require rain splash for spread to new leaves.

Leaves must be wet for most fungal spores to germinate and infect (spores of powdery mildew require only high humidity for infection). Moist conditions, particularly warm moist weather, will favour disease development in the spring period.

A year of particularly severe disease may result from very favourable seasonal conditions. This can result in very high levels of inoculum carryover. Above average disease risk may occur in seasons following high disease years.

Cereal crop production has evolved around the characteristically dry summer conditions that are typical of southern Western Australia. This period is critical to break the disease cycle of cereal rust diseases. Rust diseases rely on living host plants and do not have a resting stage. Host plants normally can not survive dry summer conditions and hence rust carryover is normally very low with a traditional dry summer. Unusually wet summer conditions can greatly increase risk of wheat rusts.

Chemical control

While disease is often present in younger crops, it is only after the flag leaf emerges and the stem stops producing further leaf material that the disease has the opportunity to catch up and progress onto the critical

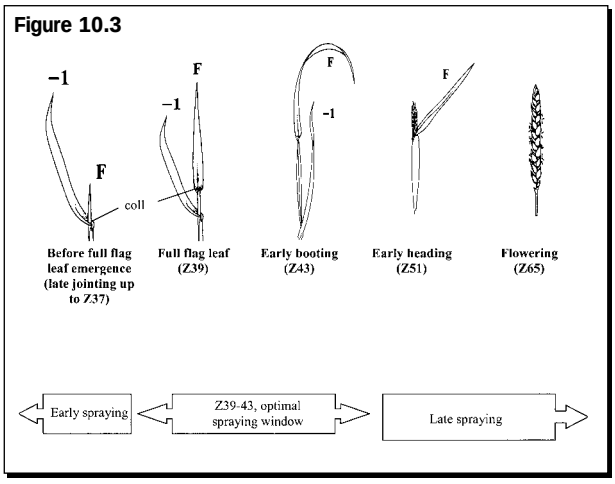
■ LEAF DISEASE *(continued)*

upper leaves. This can be early August in northern crops or later in southern crops. Seasonal conditions determine how quickly this happens.

Seed dressings can control seed borne diseases and long acting seed dressings prevent very early build up of some diseases such as leaf rust. However seed dressings are generally ineffective in controlling disease increase at later crop stages.

When disease levels increase in later crop stages the most profitable fungicide use is achieved by a single well timed spray. The optimum timing is generally between flag leaf emergence and head emergence (Figure 10.3). Spraying will be most effective if done before the upper 2-3 leaves become diseased. Application to upper canopy leaves shortly after those leaves develop, protects the leaves from infection and slows the rate of disease development on those leaves.

Figure 10.3



Spray timing.

Depending on rates of application and disease severity the protection delays disease development by 3-6 weeks. This maintains photosynthetic leaf area during grain filling. Under conditions of severe disease development it may be necessary to apply two sprays to slow disease sufficiently. After head emergence (that is, flowering or later) spraying is much less likely to be economic.

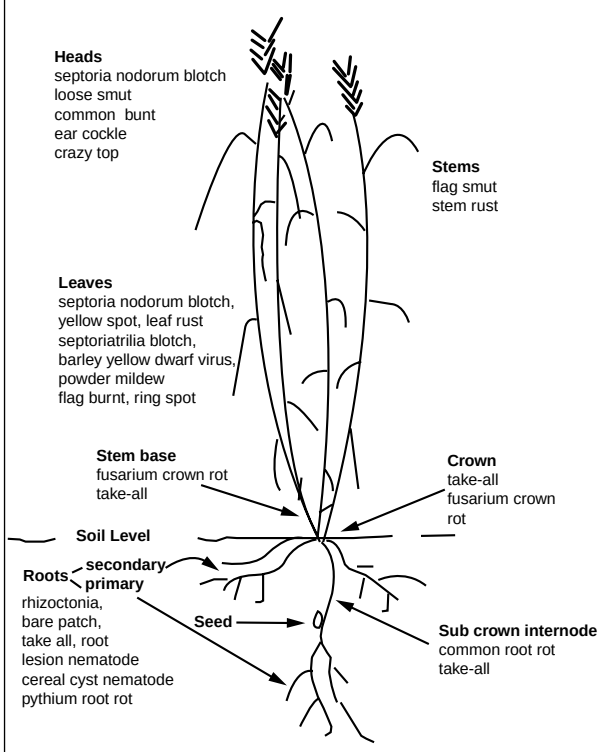
Other agronomic factors

Seeding rates and nitrogen nutrition are other factors that can affect leaf disease in high yield situations. Increasing plant density through increased seed rates can change the micro-climate within the crop which may favour leaf disease slightly.

Additional nitrogen, by favouring lush crop growth, generally favours leaf disease. However, reports on the effects of nitrogen vary and prediction of disease behaviour in particular situations is not possible.

It is likely that the impact of these factors is smaller than agronomic factors such as sowing date, varietal maturity and resistance.

Figure 10.4



Wheat plant parts and the diseases that develop and express on them.

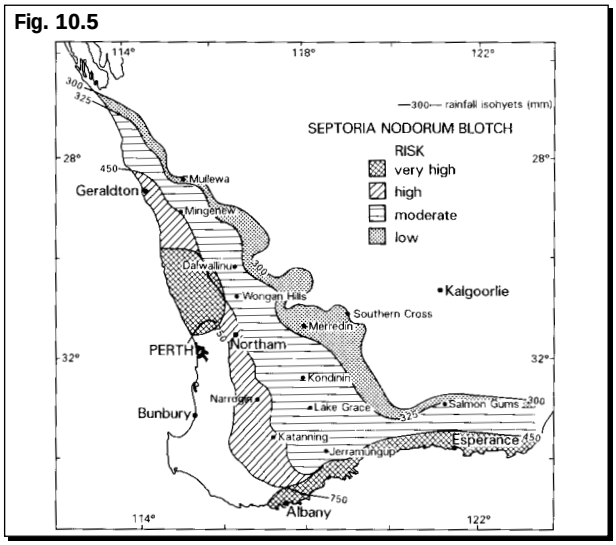
■ OCCURRENCE, RECOGNITION AND CONTROL

Septoria nodorum blotch

Occurrence

Septoria nodorum blotch is caused by the fungus *Phaeosphaeria (Stagonospora) nodorum*. It occurs throughout the wheatbelt, particularly in high rainfall areas and is most damaging in warm moist conditions (Figure 10.5). Infection late in the crop's life can hasten maturity and reduce the time available for grain filling, leaving shrivelled grains. Yield losses vary widely and can be from 30 to 80% in severe situations while losses between 5 and 15% are more common.

Fig. 10.5



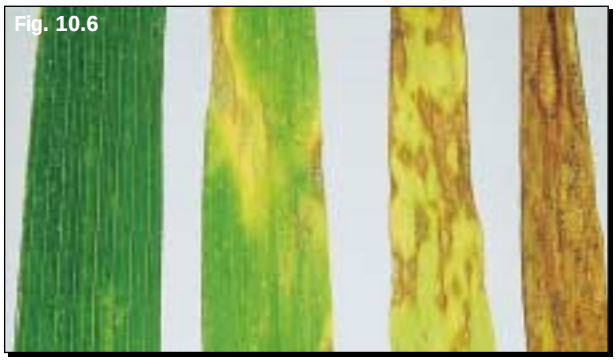
Septoria nodorum blotch distribution.

Recognition

The disease causes blotches on the leaves that are yellow or tan/brown in colour and oval in shape (Figure 10.6). The blotches enlarge and become grey in colour with age, and the leaves begin to die. Within the blotch there may be very small grey/brown fruiting bodies that appear as specks. In young crops, infection tends to occur on the lower leaves however, after booting the infection will be seen on the four highest leaves.

Towards the end of the cropping season the disease can spread into the glumes and on the stems of the plants. Heavy infection can cause blotching over the whole ear, leading to shrivelling of grain and loss of seed at harvest.

Fig. 10.6



Septoria nodorum blotch symptoms.

Life cycle

Septoria nodorum blotch is caused by two stages of the same fungus. The sexual stage, *Phaeospaeria nodorum*, occurs on infested stubble. The sexual ascospores are released under wet conditions in winter. They infect wheat leaves of the planted crop. Infection depends upon leaves remaining wet for intermittent or continuous periods of 6-12 hours. Spores produced on stubble are dispersed over long distances. In this situation, disease establishes in neighbouring crop at early stages and is able to increase to damaging levels by the time the grain is filling.

The asexual stage, *Stagonospora nodorum*, produces its fruiting bodies on leaf tissue killed by the fungus and acts to spread the disease into new crop foliage. The spores are spread by rain splash. Thus this stage is responsible for the spread of the disease within the crop.

Seed can become infected if moist conditions occur late in the season. Infected seed can carry infection into the next crop but the effect of this is very minor compared to other sources of inoculum.

Control

Rotation is important in reducing the inoculum levels. Wheat, durum and triticale can become infected. Rotate with another cereal crop, legume, pulse or pasture crop.

Varieties with partial resistance to septoria nodorum blotch are useful in the management of this disease. For best results, seek varieties that combine resistance to other common leaf diseases in your area.

Avoid early sowing with susceptible varieties in medium to high risk areas. Foliar fungicide can be used to control the disease. Spraying aims to minimise the amount of disease on the upper 2 to 3 leaves and head (see Chemical control section, above). Yield loss will be severe if most leaf area is killed before the grain has filled.

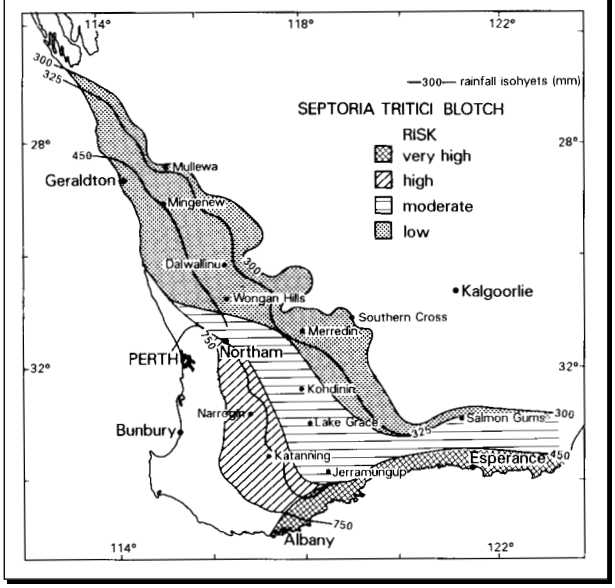
■ OCCURRENCE, RECOGNITION AND CONTROL *(continued)*

Septoria tritici blotch

Occurrence

Septoria tritici blotch is caused by the fungus *Mycosphaerella (Septoria) graminicola*. It occurs throughout the wheatbelt, but particularly south of Perth where the growing season is cooler (Figure 10.7). It is most serious in mild conditions and it becomes less active towards the end of the season except in cool areas. It rarely attacks heads and glumes. Yield losses vary widely and can be from 30 to 50% in severe situations but losses between 5 and 15% are more common.

Fig. 10.7



Septoria tritici blotch distribution.

Recognition

This disease causes irregular blotches that can be elongated and not oval as in septoria nodorum blotch. The blotches have a narrow yellow margin. Minute black fruiting bodies can be seen in rows between the veins of the affected leaf (Figure 10.8). In young crops, infection tends to occur on the lower leaves, however, after booting the infection will be seen on the four highest leaves.

Infection late in the crop's life can hasten maturity and reduce the time available for grain filling, causing shrivelled grains.

Life cycle

Septoria tritici blotch is caused by two stages of the same fungus. The sexual stage, *Mycosphaerella graminicola*, occurs on infested stubble. The sexual ascospores are released under wet conditions in winter. They infect wheat leaves of the planted crop. Infection depends upon leaves remaining wet for intermittent or continuous periods of 6-12 hours. Spores produced on stubble are dispersed over long distances. In this situation, disease establishes in neighbouring crop at early stages and is able to increase to damaging levels by the time the grain is filling.

Fig. 10.8

Septoria tritici blotch symptoms.

The asexual stage, *Septoria tritici*, produces its minute black fruiting bodies on leaf tissue killed by the fungus and acts to spread the disease into new crop foliage. The spores are spread by rain splash. Thus this stage is responsible for the spread of the disease within the crop.

Control

The use of rotations with other crops such as triticale and barley, legumes, pulses and pastures will reduce the level of inoculum carried over in subsequent years.

Use resistant varieties as this reduces the inoculum level within the crop and reduces the carryover on stubble from one season to the next.

Avoid early sowing with susceptible varieties in medium to high risk areas (this is dependent upon the rainfall conditions for those areas).

Foliar fungicide can be used to control the disease. Fungicides are generally more effective at controlling this disease than septoria nodorum blotch. Spraying aims to minimise the amount of disease on the upper 2 to 3 leaves and head (see Chemical control section, above). Yield loss will be severe if most leaf area is killed before the grain has filled.

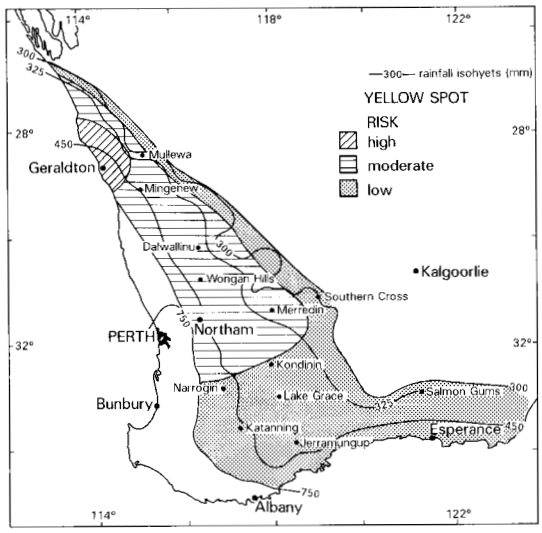
■ OCCURRENCE, RECOGNITION AND CONTROL *(continued)*

Yellow spot

Occurrence

Yellow spot occurs throughout the wheatbelt but is more serious north of Perth (Figure 10.9). Yield losses vary widely and can be from 30 to 50% in severe situations but losses between 5 and 15% are more common.

Fig. 10.9



Yellow spot distribution.

Recognition

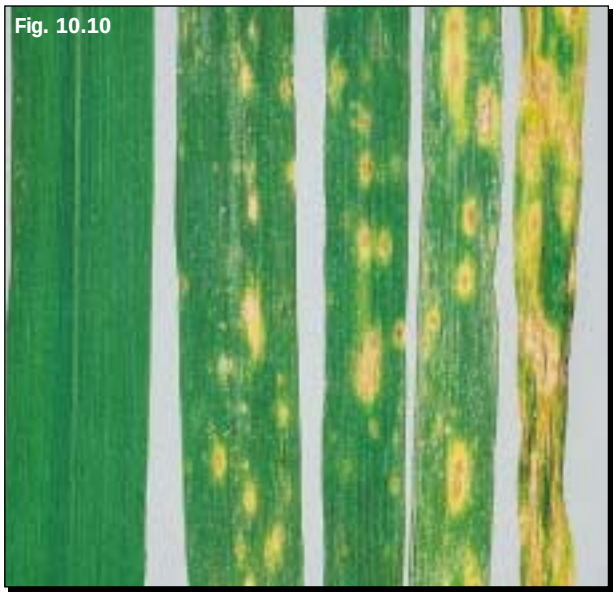
The disease starts as small areas of yellowing leaf tissue. As the areas grow, the centre turns brown but the edges remain yellow. Individual spots can vary in size or shape. When the lesions occur near the leaf tip or join the leaf dries out and withers. In young crops, infection tends to occur on the lower leaves. After booting the infection will be seen on the four highest leaves (Figure 10.10). The disease can be severe at any stage of crop development.

Seed can become infected with the fungus in moist conditions late in the season. Severe yellow spot disease causes pink grain which affects crop marketability but does not carry disease into the next crop if used as seed.

Life cycle

Yellow spot is caused by two stages of the same fungus. The sexual stage, *Pyrenophora tritici-repentis*, occurs on infested stubble as indicated by the telltale appearance of its fruiting bodies. These can be seen on infested stubble in autumn and early winter as black, raised, oval bodies about the size of a pin head. In heavily infested stubble many fruiting bodies are produced, making the straw feel like sandpaper. These release ascospores under wet conditions, which then infect wheat leaves of the planted crop. Infection depends upon leaves remaining wet for more than 6 hours. Because spores produced on stubble are dispersed over short distances, severe disease usually only occurs where wheat is double-cropped. In this situation, disease establishes in the crop at very early stages and is able

Fig. 10.10



Yellow spot symptoms.

to increase to damaging levels by the time the grain is filling.

The asexual stage, *Drechslera tritici-repentis*, produces its spores on leaf tissue killed by the fungus and acts to spread the disease into new crop foliage. They are spread by wind and rain splash. Thus this stage is responsible for the spread of the disease within the crop.

Control

Rotation is important in reducing the inoculum levels. Wheat, durum and triticale can become infected. Rotate with another cereal crop or legume, pulse or pasture crop.

Varieties with partial resistance to yellow spot are useful in the management of this disease. For best results, seek varieties which combine resistance to other common leaf diseases in your area.

Avoid early sowing with susceptible varieties in medium to high risk areas.

Foliar fungicide can be used to control the disease. Spraying aims to minimise the amount of disease on the upper 2 to 3 leaves and head (see Chemical control section, above). Yield loss will be severe if most leaf area is killed before the grain has filled.

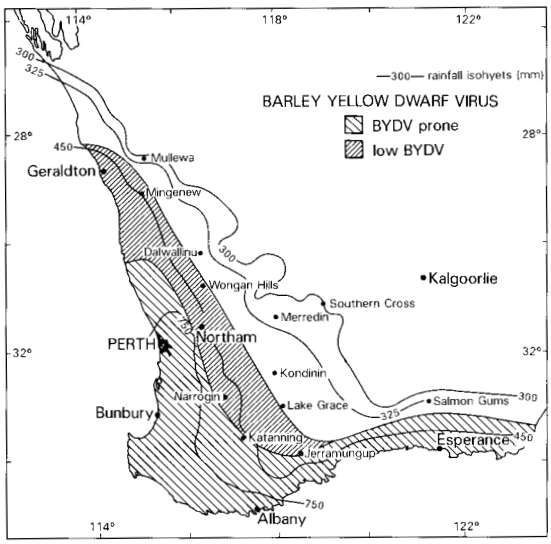
■ OCCURRENCE, RECOGNITION AND CONTROL *(continued)*

Barley yellow dwarf

Occurrence

Barley yellow dwarf is caused by barley yellow dwarf virus (BYDV). Yield losses may be 10-50% if infection and spread occurs early in the growing season. Then the proportion of shriveled grain increases, affecting quality. BYDV is spread to cereal crops from reservoirs of infection in wild or pasture grasses or cereal volunteers by grass and cereal aphids. The oat *(Rhopalosiphum padi)* and corn *(R. maidis)* aphids are the most important vectors. (Aphid descriptions can be found in the insect pests section.) BYDV affects wheat, oats, barley, triticale and pasture grasses. The virus must survive the summer in living cereals or grasses in places such as roadside ditches, creeks, soakaways and irrigated gardens. The extent of BYDV risk is largely dependent on the amount of rainfall before the growing season. With greater rainfall in late summer and early autumn (Feb-April) the extent of grass and crop volunteer survival increases. Early build-up of aphids before the growing season on plant material infected with virus leads to early arrival of virus-carrying aphids in crops. High annual rainfall zones (>500mm) are at most risk, especially when perennial grass hosts of BYDV, such as Couch, Veldt grass and Paspalum, are present (Figure 10.11). However, other rainfall zones may become high risk if they experience regular summer rainfall events. In years with dry conditions in February and March, the risk of infection is low and spraying may not be needed even in high-risk areas.

Fig. 10.11



Barley yellow.

Recognition

The symptoms of BYDV on wheat can be difficult to recognise because they are similar to some nutrient deficiency symptoms. In addition, there may be differences in sensitivity between varieties. Virus symptoms take at least three weeks to appear after infection, longer in cold weather. Wheat infected at the seedling stage usually develops a slight to severe yellowing between veins (interveinal chlorosis), some tip necrosis and occasional serration down one margin of the third and fourth leaf. When infection occurs before the end of tillering, symptoms include pronounced stunting, an increased number of poorly developed, often sterile tillers, reddening of the flag leaf (Figure 10.12), delayed maturity, abortion of terminal spikelets, shriveled grain and decreased yield.

Fig. 10.12

Barley yellow dwarf virus symptoms.

Distinct patches of infected plants may be seen in the crop, expanding as the season progresses. These are formed when winged aphids bring BYDV into the crop (primary spread) and aphids produced on the infected plants then spread the virus to neighbouring plants (secondary spread).

Wheat infected after tillering may show no obvious leaf symptoms nor decrease in plant size, but maturity may be delayed, the grain yield slightly diminished and the grain slightly shriveled.

Control

Control is achieved by preventing potential aphid vectors from feeding in the crop. Once a plant is infected with BYDV there is nothing that can be done to remove the infection. Management strategies that help to decrease losses include:

- sowing BYDV-tolerant varieties if available
- avoid very early sowing to avoid the autumn aphid flight
- direct-drilling into stubbles to conceal bare earth: winged aphids are especially attracted to small plants with bare earth around them
- strategic application of insecticides to eradicate aphids within the crop and prevent migrating aphids from settling and feeding on crop plants.

It is vital to prevent spread of barley yellow dwarf virus (BYDV) during the first 8 – 10 weeks after crop emergence. Usually this means applying insecticides before aphids and/or BYDV symptoms can be easily seen. This is

■ OCCURRENCE, RECOGNITION AND CONTROL *(continued)*

because considerable BYDV spread can occur with low aphid numbers, and virus symptoms are difficult to see in winter. Five years of insecticide experiments with a range of cereals in WA, showed that foliar sprays of synthetic pyrethroids at 3 and 7 weeks after full crop emergence decreased BYDV spread by up to 87% and increased grain yields by up to 41%. These pyrethroids (e.g. alpha-cypermethrin (Dominex or Fastac) or beta-cyfluthrin (Bulldock)) control BYDV better than pirimicarb or dimethoate because they not only kill aphids but also have an anti-feeding effect that deters new aphids from feeding for a further 3-4 weeks. The cost of spraying can often be reduced, as pyrethroids may be tank-mixed with many of the autumn-applied herbicides. Controlling aphids with synthetic pyrethroids early to stop BYDV spread can also prevent them building up sufficiently to cause feeding damage in spring. However, in bad aphid years applications of insecticides from other chemical groups may be required in spring if feeding damage becomes a problem in cereal crops.

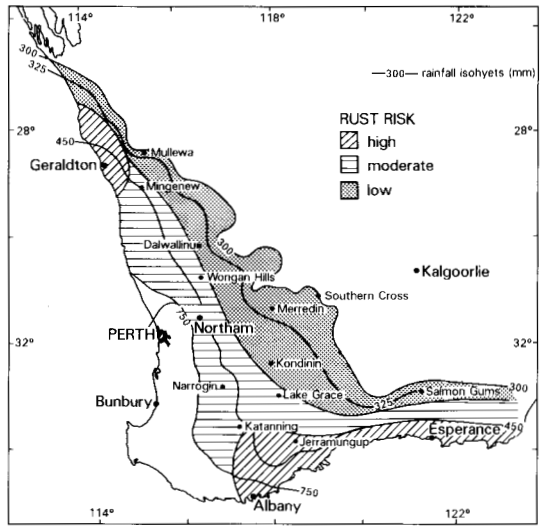
■ OCCURRENCE, RECOGNITION AND CONTROL *(continued)*

Wheat rusts

In Western Australia, rust has been a sporadic problem for wheat growers. Since the first recording of stem rust in Western Australia in 1906, there have been less than 10 epidemics. Small outbreaks of stem rust are more common and can cause severe losses over a limited area. Since the first leaf rust epidemic in Western Australia in 1992 significant outbreaks of this disease have recurred.

Rusts require living plants on which to grow and reproduce, so they must continually infect new hosts. To infect crops during the season they must survive over summer by infecting volunteer cereals or grass hosts. This occurs during seasons where summer rainfall is plentiful for volunteer cereals or weed hosts to survive. Dry summer conditions usually preclude significant carryover of rust (Figure 10.13).

Fig. 10.13



Rust risk.

The three types of rusts that can occur on wheat are stem, leaf and stripe rust. In the field, the shape and colour of the pustules (Table 10.12) can distinguish the type of rust. It is important to submit samples of rust to AGWEST. These are submitted to Sydney for typing. This then informs us if the rusts are changing in terms of resistance and helps the breeding program in developing varieties resistant to rust.

So far, stripe rust (a serious disease in the Eastern States) has not crossed the Nullarbor. Its arrival in Western Australia may increase the importance of rust control here.

Table 10.12. Distinguishing features of the wheat rusts

Pustule character	Stem rust	Leaf rust	Stripe rust
Colour†	Reddish brown	Orange brown	Yellow
Shape	Oval to elongated with conspicuously tattered stripes edges	Circular to oval	Small, circular, in yellow
Location on plant	On both sides of leaf, on leaf sheaths, stems and outside of head	Chiefly on upper surface of leaf	Chiefly on upper surface of leaf, on leaf sheaths, awns and inside of glumes

† Colour depends on the freshness of the pustule. Most spores are produced overnight so that pustules are best observed in the morning before spores are spread by wind.

■ OCCURRENCE, RECOGNITION AND CONTROL *(continued)*

Wheat stem rust

Occurrence

Wheat stem rust *(Puccinia graminis* f.sp. *tritici)* can infect wheat, durum wheat, barley, triticale and some grasses including barley grasses *(Hordeum* spp.) and common wheat grass *(Agropyron* scabrum). It is potentially the most damaging rust in Western Australia.

Epidemics will occur when summer and autumn rains allow wheat or barley volunteer plants to survive through the summer. Crop infection occurs when the temperatures range from 15-30˚C and dews occur. The disease can cause severe crop loss in a short amount of time at the end of the season.

Recognition

Stem rust usually occurs on the stem, and can occur on the leaves (both sides), leaf sheaths or in severe infections on the head. (Figure 10.4) Plants will have large pustules full of reddish-brown powdery spores. The pustules will be oval or elongated in shape. Towards the end of the season when infections are old these will change to black in colour.

Stem rust symptoms

Control

Remove volunteer cereal crops, the green bridge, to prevent the carryover and buildup of inoculum during the summer months. If inoculum levels are reduced during the non-cropping phase, infection is unlikely to occur early in the cropping season.

Use resistant varieties to reduce inoculum buildup during the cropping season. A reduction of inoculum during the cropping season reduces the carryover load during the summer months.

When stem rust is detected in susceptible cultivars –

- prior to flowering. Apply a high rate of fungicide as soon as possible.
- after flowering. Apply fungicide as soon as possible, use a low rate if the disease incidence is below 10% (up to one stem in 10 has any stem rust).
- For stem rust incidence above 10%, spray with a high rate of fungicide if the crop is before mid grain fill and with a standard rate if the crop is at mid to late grain filling

In Western Australia sporadic rust outbreaks may require the combinations of the above strategies.

■ OCCURRENCE, RECOGNITION AND CONTROL *(continued)*

Leaf rust

Occurrence

Wheat leaf rust *(Puccinia recondita* f.sp. *tritici)* is specific to wheat and triticale. A single pathotype has dominated in W.A. since 1990 and became epidemic in 1992 and 1999. Wheat leaf rust regularly survives the non-cropping summer in varying quantities, usually sufficient to occur at least to a limited extent (particularly in southern regions) each year. The disease develops rapidly between 15 and 22˚C when moisture (including dew) is non-limiting. The highest yield increase attributed directly to control of leaf rust in Western Australia is 37%. However the disease is synergistically damaging in combination with septoria leaf blotches. In Esperance in 1992 early severe leaf rust in combination with very severe septoria nodorum blotch induced 90% loss. Leaf rust does not affect other cereals and is not hosted by other cereals.

Recognition

There are small circular to oval pustules restricted to the upper surfaces of leaves (Figure 10.15). Spores are light brown in colour. The pustules will darken as the infection ages and the spores will appear black in colour. Later in the season, the infection can spread to the leaf sheaths.

Leaf rust symptoms.

Control

Control measures that are the most effective are similar to those mentioned in the above section on stem rust. The use of resistant varieties in areas that are prone to leaf rust (ie higher rainfall areas), combined with the control of volunteer wheat during the summer months, will reduce the inoculum levels and hence risk of early infection for susceptible varieties.

- during seedling stage. Monitor infection, if there is evidence of increasing severity during winter (rust progress exceeds plant growth and upper leaves become infected) apply a fungicide spray at early stem elongation (Z31/32). Recommence monitoring after 4 weeks and if necessary apply a further fungicide spray if leaf rust is detected on flag-3 leaf at or soon after flag leaf emergence. The risk of other diseases at this stage could influence choice of fungicide and rate.
- during stem elongation phase. At low severity, monitor and delay control until early flag leaf emergence unless rapid build up is observed. At moderate to high severity on middle leaves, apply fungicide during stem elongation.
- at flag leaf emergence but prior to flowering. Apply as soon as possible if leaf rust severity is moderate to high on lower leaves.
- after flowering a response to fungicide is unlikely.

■ OCCURRENCE, RECOGNITION AND CONTROL *(continued)*

Wheat stripe rust

Occurrence

Stripe rust *(Puccinia striiformis* var. *striiformis)* mainly infects wheat, but can occasionally be found on barley and triticale and on a wide range of grasses such as barley grass *(Hordeum leporinum)*, common wheat grass *(Agropyron scabrum)* and prairie grass *(Bromus uniloides)*.

It was first reported in Australia in 1979 and has since spread throughout the wheatbelt of eastern Australia, coming as far west as Ceduna, South Australia.

Stripe rust does not occur in Western Australia, but could invade at any time. If you suspect that you have stripe rust, submit a sample to Agriculture Western Australia immediately.

Recognition

There may be yellow patches within the paddock. These are usually 1-10 metres across. On the leaves the pustules are scattered on young plants while in older plants they will form in stripes along the leaf veins (Figure 10.16). The spores are yellow to orange in colour. If you rub the leaf the spores will leave a yellow coloured smear on your finger. The infection can spread to the head preventing seed from forming or becoming shrivelled.

Stripe rust symptoms.

Control

The use of resistant varieties in areas that are prone to stripe rust (ie cooler higher rainfall areas), combined with the control of volunteer wheat during the summer months, will reduce the inoculum levels and hence risk of early infection. Optimum temperatures for stripe rust are less than leaf and stem rusts (most rapid development between 10 and 15˚C) and earlier fungicide control of winter epidemics is more commonly required for this disease.

■ OCCURRENCE, RECOGNITION AND CONTROL *(continued)*

Wheat smuts

Fungi which parasitise the host plant and produce masses of soot-like spores in the leaves, grains or ears cause smut diseases.

Smuts have one of two distinct life cycles. It is important to know the type of smut and its life cycle so that the best means of control can be determined. Smut may be borne either on the inside or outside of the seed.

The smuts that are borne externally on the seed are:

- Bunt of wheat *(Tilletia laevis* and *T. tritici).*
- Flag smut of wheat *(Urocystis agropyri).*

And there is one smut of significance that is borne internally. This is:

- Loose smut of wheat *(Ustilago tritici).*

Bunt (covered smut)

Occurrence

Although very rare, bunt is potentially the most important smut disease of wheat because there is a nil tolerance level for bunt in wheat delivered to Co-Operative Bulk Handling Ltd. Bunt is extremely difficult to detect in the field and could remain undetected in harvested grain if present at very low levels. If it is seen or suspected it should be reported to Agriculture Western Australia.

Recognition

Bunt is difficult to observe except near crop maturity. Wheat plants infected with bunt are usually slightly stunted. The glumes on heads of infected plants may be spread apart more than on healthy heads. Infected kernels are greyish brown and when the fragile seed coat is crushed or broken, the soot-like spores have a characteristic stinking fishy odour.

During crop harvest, spores may also fall on the soil and remain dormant until the next crop is sown. As the seedlings germinate, the spores infect them. This soil-borne phase is an important source of infection.

Control

A regular fungicide seed dressing program is recommended for prevention of bunt.

Flag smut

Occurrence

Flag smut *(Urocystis agropyri)* occurs throughout the wheat belt in Western Australia.

Recognition

This disease is difficult to detect early in the growing season. Affected plants are often stunted and affected leaves may be curled and distorted. The spore masses can be seen as dark streaks running along the leaves and leaf sheaths, usually from about booting. Initially the spore masses are under the surface, but break through revealing distinct streaks of sooty spores on the leaves (Figure 10.17). Flag smut is the most widespread smut of wheat. Farmers growing susceptible varieties should be on the look-out for this smut. Flag smut may also be detected after harvest on standing stubble.

During harvest, the smut spores contaminate healthy seed, but remain dormant on the outside of the seed during storage. As the seed germinates, the spores also germinate and infect the seedling, growing inside it and eventually forming smutted heads or leaves (in the case of flag smut). Pickling seed with fungicide kills the spores and controls externally seed-borne smuts.

During crop harvest, spores may also fall on the soil and remain dormant until the next crop is sown. As the seedlings germinate, the spores infect them. This soil-borne phase is an important source of infection.

Flag Smut symptoms.

Control

Resistant varieties should be used when possible. For susceptible varieties a regular fungicide seed dressing program is recommended for prevention of flag smut. An appropriate seed dressing must be used to control soil-borne phases of this disease. Crop rotation will reduce soil-borne carryover but a break of two years or more will be necessary to have a significant effect.

Loose smut

Occurrence

Loose smut is generally confined to high-medium rainfall areas of the wheat belt in Western Australia.

Recognition

Loose smut of wheat *(Ustilago tritici)* is carried as a small colony of fungus inside the seed rather than as a spore on the seed coat. When infected seed germinates, the fungus becomes active and grows slowly in the growing point of the plant.

Diseased plants appear normal until heading, but may be taller and mature earlier than surrounding healthy plants. The fungus now grows rapidly and forms a compact spore mass to replace the cereal head.

The black powdery spores blow away to leave a bare stalk. The spores are released as the rest of the crop is flowering and they infect the developing grains of healthy heads, remaining dormant in the grain until the seed is sown the next season.

Control

A regular fungicide seed dressing program is recommended for prevention of loose smut.

Where more than 5% of heads show loose smut infection (infection is very high), new seed should be bought from a clean source and treated before use.

■ OCCURRENCE, RECOGNITION AND CONTROL *(continued)*

Other diseases of wheat

Powdery mildew

The fungus *Blumeria graminis* f.sp. *tritici* causes powdery mildew. Powdery mildew had been economically unimportant but in recent years infections in wheat have worsened. The fungus is evident as a whitish powdery growth on the upper surface of leaves and leaf sheaths. As the infection ages there is a yellowing of the infected tissue, and the infected area turns a dull grey colour with small black specks present. Heads may become affected. It prefers humid conditions or dense crops with high nitrogen levels. The fungus survives on crop residues. Increased severity of powdery mildew infections in wheat may have resulted from increasingly productive crops, stubble retention or increasing varietal susceptibility. Control is achieved via less susceptible varieties while the potential value of fungicide sprays and seed treatments is currently unclear. (Figure 10.18).

Powdery mildew symptoms

Ring spot

The fungus *Pyrenophora semeniperda (Drechslera campanulata)* infects leaves producing small spots with dark brown rims, which typically have pale brown centres. It occurs throughout the wheatbelt but normally does not reach damaging levels. Infection in young crops is common. The fungus infects many grasses and carries over on residues and symptoms will frequently be seen in crops after pasture.

Downy mildew

Downy mildew is caused by the fungus *Sclerophthora macrospora*. The fungus is soil-borne and carries over in host residues. In very wet to waterlogged conditions spores infect young wheat plants. The disease is damaging to individual plants producing thickened leathery twisted leaves and the heads are twisted, similar to damage induced by hormone weed killers. The frequency of infection is very, very low, and confined to areas subject to waterlogging or flooding. Control is not warranted.

Ergot

This disease is caused by the fungus *Claviceps purpurea*. The fungus survives in the soil for up to one year, producing spores that infects plants during flowering. Infection is favoured by cool wet weather during flowering. Ergots are black in colour and replace the grain in the seed head. This is toxic to animals and to humans. It is important to control grass weeds where the fungus can survive, around crops.

Ear cockle or seed gall nematode

This disease is caused by the nematode *Anguina tritici*. On plants, the heads appear normal but removal of glumes will reveal seed galls instead of normal grains. A fungus *(Dilophospora alopecuri)*, which is carried with the nematode, causes twisted and distorted leaves and ears. These are the best indicators that the nematode may be present. At heading, the plants are stunted and slow to mature.

The developing seed of plants with twisted leaves should be examined for galls. In harvested seed, galls are dark and do not crush readily like bunt.

The nematode larvae hatch from the galls and climb up the plant. The young larvae attack the growing point and embryo flower head causing grains to be replaced by nematode galls. At harvest, galls are mixed with seed or fall to the ground, providing effective means of spread and survival.

Control is achieved by not sowing infested seed and by eliminating soil-borne larvae by not cropping wheat for two years. The disease is very rare in Western Australia.

■ ROOT DISEASE

Principles and management

Disease causing microorganisms that affect roots, crowns and stem bases of cereals are widely distributed in agricultural soils in Western Australia. Their impact varies across regions in response to management and seasonal conditions. Slow spread and disease build up and patchy distribution are features of the biology and life cycle of root diseases. Most are limited to one infection cycle in a season and are usually not dispersed in the same way as leaf diseases. For this reason they can be effectively managed when recognised and understood. However their insidious development, often remaining inconspicuous during build-up, means that they can go unnoticed or appear to "come from nowhere". Uneven inoculum dispersal, varying crop growth, weed infestation or soil environment can result in patchiness or uneven crop growth that can be confused with other environmental effects.

A general feature of root diseases is that they are able to attack a wide range of plant species. Wide host range requires special consideration for disease management. A systems approach that integrates root disease management with other agronomic factors will be the key to successfully minimising the most common and important root diseases of cereals.

Rotation

This is the most important factor in root disease management. The key to successful rotational management is to have cropping sequences that include non-hosts or poor hosts for key diseases. As a general rule, the greater the diversity of non-cereal crop-rotation-species, the greater the impact on root disease carryover. (Figure 10.19).

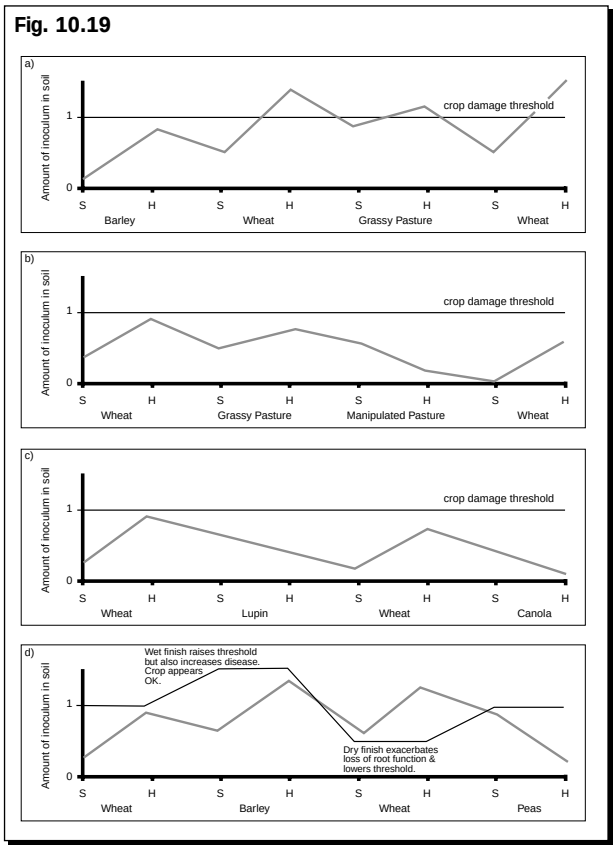
During a wheat phase root disease has the opportunity to increase. The amount of damage will depend on the level of disease and interactions with seasonal factors. As the crop matures, the pathogen becomes protected within the infected roots and crowns. A breakdown of root and crown tissue would expose the pathogen to attack by other soil microorganisms. For much of the non-cropping season, however, soil conditions are dry and soil microorganism activity is low, hence most of this breakdown occurs in the following growing season, rather than between seasons. Infected plant residues, the inoculum for future disease initiation, gradually rots away over a 12-18 month period in the absence of a host to re-infect.

The diseases, take-all and crown rot, are two fungal diseases that have adapted to survival in soil by attacking a range of cereal and grass hosts. Both fungi readily attack wheat but also barley and numerous common grasses. For this reason effective management of these diseases requires non-cereals in the rotation. It is very important to control grass weeds in non-cereal rotation crops and pastures for effective lead-in management for the next wheat (or barley) crop.

Diseases with broad host ranges require greater care when planning cropping sequences. Root lesion nematodes are able to attack both cereals and non-cereals but do have preferences for different hosts. Some alternate crops, such as canola, can allow some root lesion nematodes to increase. Growing crops such as field pea, lupin and faba bean will generally discourage root lesion nematodes. The rhizoctonia bare patch fungus is able to infect a wide range of hosts and hence can not be managed by rotation.

Appropriate crop rotations will ensure yield loss will be minimised by keeping disease levels low. In disease prone areas, it may be necessary to alternate with a non-host crop for every susceptible crop grown while in some areas relevant break crops may be required less frequently.

Figure 10.19 – Effective rotations permit long periods of inoculum decline (long shallow saw-teeth figure b,c) compared to inoculum maintenance (a). d) Seasonal conditions influence disease build up and expression.



Factors affecting root disease development and expression.

Tillage

It is possible that multiple tillage practices in use before the adoption of pre-plant herbicides and direct drilling resulted in some breakdown of infected plant debris and destruction of root disease inoculum. However these effects were probably small, particularly in rotation cropping, hence would not outweigh the agronomic benefits of current systems of crop establishment.

OCCURRENCE, RECOGNITION AND CONTROL *(continued)*

Tillage is an important means of managing rhizoctonia bare patch. This fungus becomes active with seasonal rains and the fungal threads (mycelia) grow through soil. Tillage disrupts these fungal threads, reducing their potential to cause infection. Tillage may also provide seedbed conditions that encourage more rapid root growth. This enables plants to better cope with some root damage from infection.

Seasonal influences

Soil moisture affects root disease directly through conditions for infection and also indirectly through the capacity of the plant to tolerate root disease. Soil moisture also affects the rate of breakdown of infected trash.

Soil moisture can directly influence the type and amount of root disease. Early in the season very wet to waterlogged conditions can favour Pythium fungi. Pythiums are soil fungi that can damage the small feeder roots. In the absence of waterlogging Pythium spores are less able to swim to developing roots and so normally do not affect plants significantly. With high but not excessive levels of soil moisture the fungi that cause take-all and crown rot are better able to infect and colonise plants.

When the root system is damaged by disease the plant is less able to take-up water and nutrients, or tolerate stresses such as waterlogging and drought. Reduced uptake will affect plant growth and these effects may be evident in early crop stages (e.g. rhizoctonia bare patch) or later during stem extension. Plants can frequently grow and tolerate a partial loss of function until there is a period of moisture stress, or until the critical grain filling time is reached. The later is often exacerbated because at this time the plant has to meet increased demands for moisture as temperatures rise. For this reason root diseases can often become more

Table 10.2 – Summarised rotation options for root disease control in wheat (adapted from Managing your right rotation).

		Possible Break Crops	
Disease	**Main Hosts**	**Non – cereals**	**Resistant cereals**
Take-all *Gaeumannomyces graminis var tritici*	wheat, barley triticale barley grass brome & silver grass	pulse crops pasture legumes oilseeds	oats
Root Lesion Nematode *Pratylenchus neglectus*	wheat & barley canola vetch medic chickpea	*lupins* peas faba beans	cereal rye triticale, durum oats
Rhizoctonia Bare patch *Rhizoctonia solani AG-8*	*All plants are hosts to some degree*		
Crown Rot *Fusarium graminearum*	wheat barley triticale grasses weeds	pulse crops pasture legumes oilseeds	
Cereal Cyst Nematode *Heterodera avenae*	wheat barley oat triticale wild oats	pulse crops pasture legumes oilseeds	cereal rye selected wheat, barley, oat and triticale varieties
Common Root Rot *Bipolaris sorokiniana*	barley wheat	pulse crops pasture legumes oilseeds	cereal rye oats

■ OCCURRENCE, RECOGNITION AND CONTROL *(continued)*

evident and induce greater effects on production under drier than normal crop finishing conditions.

Soil type

Soil chemical, physical and biological properties also influence soil pathogens directly. The take-all fungus is better adapted to alkaline soil conditions and some soils (e.g. alkaline black wattle sands south of Geraldton) are prone to this disease. Rhizoctonia bare patch is usually more pronounced on very sandy soils. Soil properties resulting in increased biological activity are believed to antagonise root diseases such as take-all and rhizoctonia in long-term no-till experiments. The basis for these influences are not well understood.

Soil types can influence the frequency of wheat cropping and this in turn influences root disease occurrence. Soil type also influences soil moisture availability, particularly during periods of moisture stress. Wheat is grown at high frequently on high clay content (heavier textured) soils in the eastern wheat belt, favouring the occurrence of fusarium crown rot, which can be more evident with mild moisture stress at grain filling.

Nutrition

Anything that helps crop growth is likely to reduce the impact of disease. Root damage will limit nutrient uptake, which may lead to deficiency and further impaired root growth.

Some pathogens are influenced by soil pH. Activities that influence soil pH, such as nitrogenous fertilisers (increasing pH) or liming (decreasing pH) may have minor influences on most root diseases. The exception is take-all, were excessive use of lime will lead to an increase in this disease. Liming to neutral pH will have no effect, but liming to pH 8 and above will increase take-all. Usually these effects are small compared to factors such as rotation and season rainfall.

Trace elements are also implicated in root disease interactions and both macro and micronutrients are important. Providing adequate nutrition makes crops better able to tolerate root disease.

Host resistance

There is limited host resistance to root diseases. In Western Australia crop rotation is more important in managing disease than host resistance. Highly effective resistance is available for cereal cyst nematode but this disease has limited distribution and importance under our diverse cropping systems. No resistance is available for take-all, fusarium crown rot or rhizoctonia bare patch while some wheat cultivars exhibit partial (moderate) resistance to some root lesion nematodes.

Chemical control

Few chemical control options are available for root diseases. Seed treatments are being sought for root diseases but conventional seed treatments used at concentrations that are required to control root disease are too toxic to young plants. To overcome this problem it is possible to apply fungicide in-furrow by mixing it with fertiliser and sowing or banding at seeding. This approach can be used to control take-all when high disease levels are anticipated. Future developments with seed treatments are possible.

■ OCCURRENCE, RECOGNITION AND CONTROL *(continued)*

Take-all

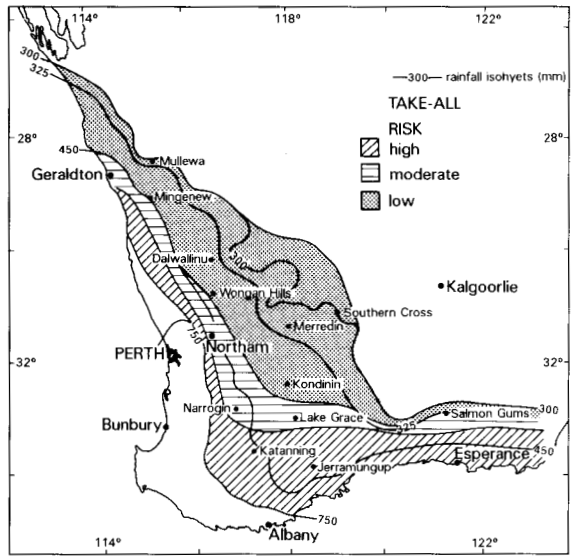
Occurrence

Take-all, caused by the fungus *Gaeumannomyces graminis* var. *tritici*, is a significant root disease of wheat and barley, it also infects oats but to a lesser extent. It is widespread throughout the wheatbelt but causes the most damage to crops in the high and medium rainfall areas (400 to 750 mm annual average rainfall) near the southern and western edges of the wheatbelt (Figure 10.20).

Along the south coast take-all may be so serious that cropping to wheat or barley is not always economically feasible.

In other parts of the wheatbelt the presence of take-all affected cereal plants and the yield loss may go unnoticed unless the cereal plants are removed from the soil and the roots examined after washing them to remove all soil.

Fig. 10.20



Take-all distribution

Recognition

Paddock appearance: In young crops, look for stunting or poor growth of individual plants or indistinct patches of up to several metres diameter. At later stages when crops have headed look for premature plant death and white-heads, particularly as soil moisture becomes limiting. Near the centre of the patches most plants are affected but the proportion decreases towards the edges. Take-all affected plants are stunted and may hay-off early causing pinched grain. In a severe outbreak of take-all, patches may overlap so that large areas of the paddock will appear to be a mosaic of varying densities of affected plants.

Plant appearance: The most common symptom of take-all is the presence of dark brown roots due to invasion by the fungus. The roots of plant suspected of being infected with take-all need to be washed thoroughly to enable symptoms to be seen. In washed roots from young plants, it is possible to see the diseased dark brown central core running through the young white roots. The roots of mature affected plants are brittle, break off short and are black. By contrast, healthy roots are long and pale. Severely affected plants have a black crust around the stem base. Removing the leaf sheath at the base of the plant may reveal this crust or just brown to black streaks or spots (Figure 10.21).

Fig. 10.21

Take-all symptoms (Green stem base is healthy).

Life cycle

The fungus colonises host plants in the winter/spring period, killing roots and destroying root function. After infected plants die the fungus remains inactive in diseased tissues such as roots and crowns while the soil is dry over summer. The following winter the fungus becomes active and re-infects newly growing host plants.

Control

The take-all fungus has a wide host range, infecting wheat and barley and to a lesser extent, oats and it also infects most volunteer and pasture grasses. Barley grass *(Hordeum leporinum)* is the most susceptible common grass, followed closely by annual ryegrass *(Lolium rigidum)* and silver grass *(Vulpia sp.)*, while brome grass *(Bromus diandrus)* is least susceptible. The susceptibility of other pasture grasses falls within the range of these common pasture grasses. The fungus does not infect non-grass pasture plants such as clover, medic or capeweed, or non-cereal crops such as lupins, pulses or canola.

Results of two long-term rotation experiments at Esperance Downs Research Station showed that there is a close relationship between the incidence of take-all in a crop and the amount of grass in the previous pasture. In these two experiments the pasture composition was altered with herbicides. Measurements taken over six years showed that the incidence of take-all over the whole crop increased by about 5% for each 100 kg/ha of grass dry matter in the previous year's pasture (measured in spring) (Figure 10.22).

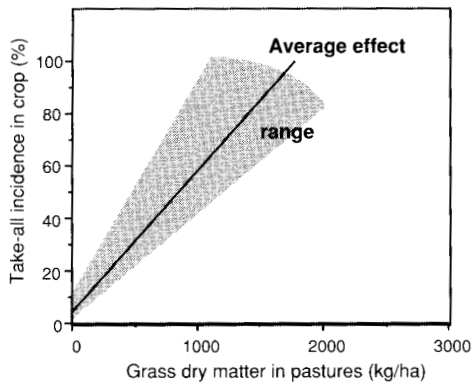
- Effective control can only be obtained by establishing a period of at least 12 months prior to susceptible cereal crops in which grasses (which carry the disease) are not

■ OCCURRENCE, RECOGNITION AND CONTROL *(continued)*

allowed to grow. Two years may be required where high grass burdens have been carried over several years.

- Grass control can be obtained in alternative crops, for example in lupins, pulses or canola or in pastures, by use of herbicides.
- Use ammonium-containing sources of nitrogen in preference to urea.
- Consider using phase pasture rotations in which the last year of pasture is managed to minimise the disease carryover into the first year of cropping.

Fig. 10.22



Pasture grass content influences on Take-all

To bring a pasture paddock into cropping following an extended pasture phase, preparation of the paddock needs to start at least one year before sowing the crop. The object is to ensure that the pasture is grass free from the start of winter in the year prior to sowing a cereal crop.

There are two options for manipulation of pasture (grass-legume mixtures) with herbicides to control take-all:

- seed set control two years before cropping; and
- selective grass control by spraying in the year before cropping

In planning either (or both) of these grass control strategies, farmers must consider the implications for developing herbicide resistant grass weeds in the paddock. In both options, broad-spectrum herbicides can be used to achieve selective grass control.

Seed set control can be achieved with either a broad spectrum or a grass selective herbicide applied when most grass in the pasture is in the early stages of flowering. This ensures that the minimum amount of viable seed is set for germination in the following year. An additional consideration is that the legume component of the pasture must set enough seed to be competitive with grasses that germinate, and to provide sufficient grazing in the following year, that is, the year of pasture before cropping.

Selective grass control can be achieved by applying either broad spectrum or selective herbicides in early winter. These must be applied at about the 6-leaf stage of the clover or medic plants in a pasture during the year before a cereal crop is sown.

After grass control, pasture production is reduced in late autumn and early winter when grazing is already in short supply. However, to complete the control of grass, grazing pressure must be maintained on the pasture to prevent tillers developing on sprayed plants and the establishment of grasses that germinate late.

Before embarking on pasture manipulation in early winter, first ensure that there are enough clover or medic plants in the pasture (that is 1,000 to 2,000 plants per square metre). This is to compensate for the loss of grass in the pasture and to smother grass plants that survive or emerge after spraying.

Herbicide must be applied as early as possible in the growing season to allow the longest time for grass root fragments harbouring the fungus to break down. Delaying herbicide application by as little as three weeks can considerably increase the amount of take-all fungus that survives to the end of the growing season.

Liming and Take-all: The severity of take-all evident in a cereal crop is influenced by the pH of the soil around the roots of growing plants. Take-all will be less severe in acid soils (ie. low pH). Liming soils to increase the pH will also make the conditions around plant roots more conducive to take-all.

A consequence of this may be that farmers suddenly notice take-all in their cereals where crops have previously appeared to be uniform. Liming soils, therefore, increases the need for rotation of cereals with broadleaf crops or grass-free pastures.

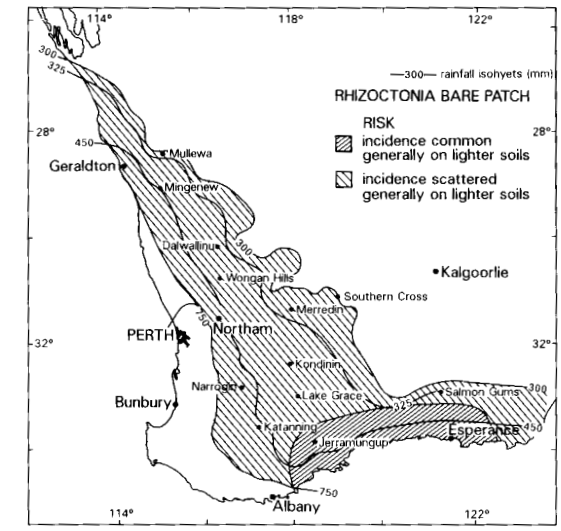
■ OCCURRENCE, RECOGNITION AND CONTROL *(continued)*

Rhizoctonia bare patch

Occurrence

Rhizoctonia bare patch, caused by *Rhizoctonia solani* AG-8, is a very important and common disease throughout the wheatbelt (Figure 10.23). The disease is most common in soils of low fertility such as acid sands and in minimum and no till situations.

Fig. 10.23



Rhizoctonia distribution.

Recognition

Bare patches appear within a crop early in the season and become more distinct as neighbouring crop continues to grow. They can vary in size from very small to several metres across (Figure 10,24). There is a distinct difference between infected plants within the patch and healthy plants outside the patch.

Infected plants within the patch are pale or very dark green, and stunted. The root systems when washed show small, brown roots with spear tipped ends.

Fig. 10.24

Rhizoctonia symptoms.

Life Cycle

Rhizoctonia survives in organic matter (mainly colonised roots) during the summer months. Following autumn rains the fungus grows out of this material to infect young seedlings. In many cases individual patches represent individual Rhizoctonia colonies that spread through soil to adjacent plants.

Control

There are no cereal varieties resistant to rhizoctonia bare patch. Barley is most susceptible followed by wheat while oats are least susceptible. Rotations with other crops will not reduce the level of disease as the AG-8 strain can grow on legumes, canola and weed species, as well as all the cereals.

Cultivation after rain and at any time just prior or at sowing reduces the impact of the disease on a new crop. In WA cultivation to 10 cm is required and improved control occurs with increasing depth and intensity of cultivation. Use of a modified combine with tynes that cultivate to 10 cm but place the seed at normal seeding depth (2-3 cm) is an effective one-pass method of controlling or significantly reducing rhizoctonia bare patch.

Increase soil fertility. This encourages better crop establishment and enables the plants to offset the root damage caused by *Rhizoctonia*, by faster root growth and development of a larger root system. Trace element deficiency can increase the disease severity.

The use of sulfonylurea herbicides increases the impact of the disease. This is because under alkaline soils the herbicide reduces root growth, thus accentuating root damage due to Rhizoctonia.

■ OCCURRENCE, RECOGNITION AND CONTROL *(continued)*

Fusarium crown rot

Occurrence

Crown rot is caused by the fungus *Fusarium graminearum* that persists in infected crop residues and can be carried over on infected grass weeds for a period of two years. It is most prevalent on heavy soils in the eastern wheatbelt.

Recognition

The disease is noticeable after flowering when scattered white-heads appear in the crop. The disease can occur as patches of plants with whiteheads. Sometimes this can be confused with Take-all, as this disease also causeswhiteheads after flowering. However, whiteheads on scattered plants is more likely to be crown rot while white-heads in patches are usually take-all.

Inspect the crown (where roots join the base of the stem) of the affected plants by peeling off the old leaf sheaths to reveal the true stem. The lower stem and sub-crown internode of infected plants has a honey-brown discoloration. Sometimes there is a pink discoloration around the crown, or under the leaf sheaths.

Life cycle

The fungus colonises host plants in the winter/spring period and disrupts the translocation of water from the roots. After infected plants die the fungus remains inactive in diseased tissues such as roots and crowns while the soil is dry over summer. The following winter the fungus becomes active and re-infects newly growing host plants.

Control

Crown rot occurs when the fungus can build up in the soil over two or more years when susceptible crops are grown in close rotation. Wheat, barley, triticale and grasses are susceptible to the disease. Long rotations with pulses, canola and grass-reduced pasture will reduce the population level. Oats can be used as a break crop because the fungus grows more slowly in oats and less inoculum is carried over into the next season.

It is important to control grass-weeds to reduce the carry over between seasons. Without rotation infected stubble should be burnt. The cultivation of soil also speeds up the decomposition of crop residues and may assist in the management in some situations.

■ OCCURRENCE, RECOGNITION AND CONTROL *(continued)*

Root lesion nematode

Occurrence

Root lesion nematodes *(Pratylenchus species)* are microscopic roundworms that feed in living root tissue of a wide range of host plant species. Several species occur in Western Australia and different species can differ in host range. In Western Australia significant root lesion nematode infestations have been diagnosed where cereals have been grown after cereal, canola, medic or subterranean clover-based pasture. Root lesion nematodes move in moist soil to locate and invade roots in which they feed and reproduce. Where conditions such as host crop and seasonal environment are favourable *Pratylenchus* populations may increase to levels damaging to crop production. *Pratylenchus* are known to occur across a wide range of soil types in the southwest agricultural areas of Western Australia. High soil populations are more common in some areas than others.

Recognition

Above ground symptoms are non-specific. Infested plants show poor vigour and growth and may occur in large or small patches that are generally less well defined than rhizoctonia bare patches. If roots are dug (not pulled) from the soil and washed brown lesions may be evident (Figure 10.25) and in heavily infested plants the roots may be thin and poorly branched. It may be difficult to distinguish between damage due to root lesion nematodes and fungal root diseases including rhizoctonia bare patch or take-all. Suspected root lesion nematode infestations can be confirmed by laboratory testing. Testing can help define the problem and determine the species of nematode(s) present. This information is important in determining how to manage a root lesion nematode infestation.

Control

Crops grown under favourable conditions will be more tolerant of nematode damage but may contribute to increased populations. Experiments in Western Australia have shown significant yield losses in both wheat (5-10%) and barley (5-20%). Losses of 5-10% may go unrecognised. Where a root lesion nematode threat exists, a range of agronomic management options can be used. No chemical control options exist.

The most effective means of reducing soil infestations of root lesion nematode (or preventing its build up) is to grow resistant crops or pasture in the rotation. Crops such as field pea, faba bean, lupin, lentil, rye, triticale, durum wheat and oats have varying degrees of resistance and so make good break crops (Table 10.3.). Growing these crops should reduce nematode density in soil. Some crops may

Fig. 10.25

Root lesion nematode symptoms.

Table 10.3. Resistance/susceptibility of major crops and pastures and their general role as break crops or host crops with respect to two nematode species (Data provided by S. Taylor SARDI, V. Vanstone University of Adelaide & G. Hollaway AgVic)

Resistant (break) crops			Susceptible (host) crops		
Plant	*P. neglectus*	*P. thornei*	*Plant*	*P. neglectus*	*P. thornei*
Faba Bean	R	MR	Medic	MS	MR-R
Field Pea	R	R	Barley	MS-MR	MR
Rye	R	Sub. clover	MR	S-MS	
Lupin	MR-R	R	Vetch	MS-MR	S-MS
Triticale	MR-R	MR-R	Canola	S	MR
Lentil	MS-MR	R	Wheat	S-MR	S-MR
Durum	MS-MR	MR	Chickpea	S	S-MS
Oats	MS-MR	-			

R = resistant, MR = moderately resistant, MS = moderately susceptible and S = susceptible

■ OCCURRENCE, RECOGNITION AND CONTROL *(continued)*

be resistant to one species but susceptible to another (e.g. canola is susceptible to *P. neglectus* but moderately resistant to *P. thornei*). Where mixed populations of *Pratylenchus* species occur crops resistant to only one species may allow the other species to increase.

There are differences between varieties for resistance and tolerance to *Pratylenchus* species. Where a root lesion nematode problem is recognised, the risk of build up and impact will be reduced if a moderately resistant or moderately susceptible variety is grown in preference to susceptible varieties. In the absence of suitable varieties with resistance, selection of a more tolerant variety will minimise the risk of yield loss, though nematode populations are likely to increase.

Control summer weeds well in advance of cropping. Maximising the pre-plant fallow period with early weed control may be important to reduce potential nematode activity before cropping. Early weed control rather than delayed sowing should be used to maximise the pre-plant fallow period.

There is little information on the effect of tillage on root lesion nematodes. In dry soil, root lesion nematodes are brittle and highly vulnerable to soil disturbance while in wet soil the nematodes are much less fragile. Reduced numbers of *Pratylenchus thornei* were found to be associated with multiple tillage in Queensland. In most circumstances contemporary tillage operations are unlikely to substantially influence nematode numbers..

Adequate nutrition will help to compensate for loss of root function caused by root lesion nematode. Loss of root function through nematode damage may also induce trace element deficiencies. In these situations application of foliar trace element sprays may alleviate a deficiency and hence improve crop yield. Where crops are known to be infested with damaging levels of nematodes, plant tissue tests may be used to check whether nutrient deficiencies are present.

■ OCCURRENCE, RECOGNITION AND CONTROL *(continued)*

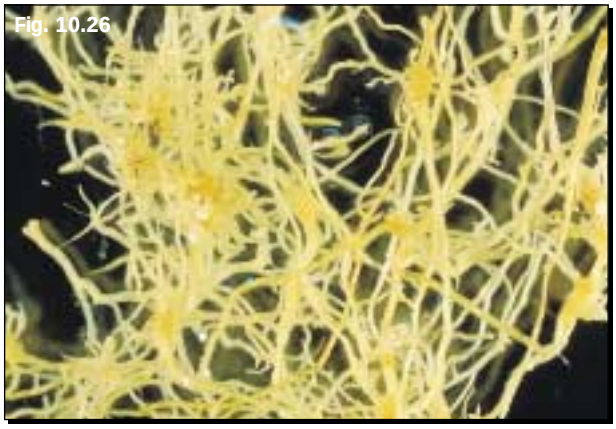
Cereal cyst nematode

Occurrence

Cereal cyst nematode (CCN), *Heterodera avenae*, is an important disease in cereals in South Australia and Victoria. It is known to occur in the northern, central and occasionally southern agricultural areas of Western Australia, but its impact is less than in eastern Australia as the disease is comparatively uncommon.

Recognition

CCN appears as patches of poor growth similar to those caused by nitrogen deficiency or water stress. Plants are stunted and yellowish, due to the lack of nutrients caused by the root damage. When examined closely the roots have small swellings (looks like knots), with many side roots protruding from these swellings (Fig. 10.26). This gives the roots a brush-like appearance. The minute white cysts may be evident in spring, turning brown as the season progresses. Soil tends to stick more closely to infected roots, so they are harder to wash clean. Affected plants are stunted, have fewer tillers and generally lack the vigour of unaffected plants. Patches can vary in size from 1 to 100 metres within a paddock.



Cereal cyst nematode symptoms.

Life cycle

Cereal cyst nematodes survive during the summer months as cysts within the soil. During autumn, when the soil temperatures drop and soil moisture levels have increased the cysts break their dormancy and the nematode juveniles begin to hatch. Hatching occurs over an eight to ten week period when the soil temperature has dropped to 12˚C. After hatching the juveniles move towards the plant roots and penetrate through the growing tips. Feeding of the juveniles causes the roots to proliferate above the damaged root. The females produce eggs within their own body and swell. These white females are visible to the naked eye. These then encyst as the soil moisture decreases to survive over the summer months.

Control

Most crop damage occurs when continuous wheat cropping is practiced. The best control is achieved through the use of crop rotation with a legume crop or with non-grass pasture. Most grasses are very good hosts to CCN, so the reduction of volunteer grasses within a pasture and the use of leguminous crops will help reduce the population of CCN. Following a severe infestation a two year break is recommended to reduce population numbers to a low level and prevent crop damage. Resistant cultivars have been developed in South Australia and Victoria and can assist management in extreme cases in Western Australia.

Sow crops early to reduce root damage. Early sown crops have a well established root system before infection occurs. Crops sown late after the break have a poorly developed root system and when the larvae hatch and infect, are less able to tolerate the disease.

Improve soil fertility. This encourages better crop establishment and enables the plants to offset the root damage caused by nematodes, by faster root growth and development of a larger root system.

■ OCCURRENCE, RECOGNITION AND CONTROL *(continued)*

Common root rot

Occurrence

The fungus *Cochliobolus sativus (Bipolaris sorokiniana)* causes common root rot. This disease is a major problem in New South Wales and Queensland. Although the fungus is widespread in Western Australia, particularly in the northern wheatbelt, it appears to cause only a minor reduction in yield.

Recognition

This disease does not cause distinctive symptoms within a crop. Infected plants are paler and stunted compared to healthy plants, and appear singularly or in irregular patches.

Roots of infected plants are brown, especially the sub-crown internode (section between the crown and the seed). This distinguishes the disease from take-all which causes blackening of the sub-crown internode and roots.

Control

Bipolaris survives on roots of grasses and as spores in the soil. Rotations with legumes, pulse or oilseed crops will reduce the build up of the fungus in the soil. A one year rotation may not always prevent crop damage. Increasing the soil fertility will reduce the impact of the disease on the crop. Oats are less susceptible than wheat, barley or triticale. It is more likely to occur when wheat and barley crops have been grown in a close rotation. Little is known about responses of Western Australia varieties to common root rot.

■ OCCURRENCE, RECOGNITION AND CONTROL *(continued)*

Pythium root rot

Occurrence

Pythium root rot *(Pythium spp.)* is most common in areas of high rainfall. Very little is known about the impact of the disease on crops in Western Australia. It is more likely to occur during wet years especially if it is very wet after the break of the season and the crops have just been sown.

Recognition

Plants are stunted, develop poorly and generally look unthrifty and nitrogen deficient. These plants may have reduced tillering and may die within the field. Plants can occur individually throughout the crop or may occur in patches where the soil is waterlogged.

The root system is stunted (looks stubby) with very few lateral roots present. The roots are soft and yellow to light brown in colour.

Control

There are no resistant varieties to the disease. A short rotation with a legume or pulse crop will not reduce the level of disease as the fungus survives as oospores in the soil for over 5 years. *Pythium* exists mainly in the top 10-15cm of soil where fine wheat roots are abundant, and where crop residues are deposited. These residues provide nutrients and moisture to the fungus.

Most crop damage occurs when rainfall is high after sowing. The disease is more severe in direct drilled crops and where stubble is retained. Avoid sowing into cold wet soils, or sowing crops directly after applying herbicides to control grass weeds.

Increase soil fertility. Plants may recover from early infection where nutrition is adequate to promote root growth. Studies in Canada have shown that the disease is worse in crops that have phosphorous deficiency.

CHAPTER ELEVEN

INSECT PESTS

Chapter Coordinator: R. Emery
Wheatbook 1 Author: Anon
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INSECT PESTS

Rob Emery

There are many insects and invertebrates to be found in wheat crops. Many cause no damage while some are even beneficial. Spiders for example, have only recently been found to play a significant role in reducing the numbers of pest insects in field crops. However it is the pest species which tend to be the most obvious.

The importance of insect pests can vary according to changing farm practices e.g. false wireworms have become more predominant as their biology is suited to stubble retention practices. Booklice or psocids have only recently become significant pests of stored grain in Western Australia, now that residual contact insecticides are rarely used.

The pests described in this chapter can cause serious damage to wheat, with major financial implications to growers, however there is also a range of exotic wheat pests which, owing to Western Australia's remoteness and our stringent quarantine laws, do not occur here. Overseas pests like the hessian fly, Russian wheat aphid and khapra beetle have the potential to be more devastating that any of our established pests. Quarantine vigilance and active surveillance must be maintained or expanded to protect the future of Western Australian wheat growers.

International markets, especially developing countries where cereals are the staple part of the diet, are becoming increasingly wary of chemical residues in wheat. Western Australia is well placed to meet these burgeoning markets because contact insecticides are not used during storage. These markets may become jeopardised, however, by increased chemical usage on-farm if field pests are not effectively managed or other pests are allowed to enter Australia.

DETERMINING THE NEED FOR CHEMICAL TREATMENT

This chapter outlines the nine major insect pests of wheat in Western Australia along with management methods that have proven practical under Western Australian conditions. Recommendations, especially chemical, are current at the time of publication. The mention of some active ingredients does not imply approval to the exclusion of others and the user bears the responsibility for correct use and is legally bound to use the chemical in accordance with the label.

The appearance of damaging population from year to year cannot usually be predicted with accuracy and in any case management and weather will affect pest numbers. It pays to become familiar with the major pests and their effect and to examine crops before damage occurs. Weekly scouting of crops is advisable bearing in mind that different pests will attack the crop at different developmental stages. For example, cockchafers and desiantha weevils will completely devour developing seedlings, while grain insects wait until the wheat has been harvested before going to work.

A sweep net is a valuable aid in determining pest numbers for aphids, lucerne flea and desiantha. The extent of cockchafer and false wireworm infestations can be calculated as number of grubs per shovelful of earth, while other pests require visual inspection.

As well as working out the likely returns from the crop and the cost of treatment it is important to consider the following:

Growth stage

The seedling stage is the most critical as relatively small pest numbers may cause rapid and extensive damage. Where large numbers of webworm or cutworm are present, it may even appear that the crop has not germinated when the pest has eaten cotyledons as soon as they appear above ground.

Crop health

A vigorously growing crop of adequate plant density can withstand considerable insect attack with little appreciable yield loss. Where sowing has been too deep or the crop is stressed for moisture, the significance of pest attack will be greater.

Management

Paddock management may have a great effect on pest numbers especially those of webworm. Paddocks which are still very grassy in April, when webworm eggs are laid, are at risk. Conventional weed control, giving a three week fallow, will give complete control of this pest, whereas numbers may increase significantly with minimum tillage planting.

Some rotations can increase the likelihood of damage by some pests e.g. cockchafers can cause severe damage to cereals following pasture but are almost impossible to find following lupins.

Biological control versus spraying

Some form of biological control invariably operates against all pests. Aphids, for instance, have many predators, parasites and diseases which may be seen and should be preserved where possible by using a selective chemical and spraying only when necessary.

When pests are at economically damaging numbers, reliance cannot be placed on biological control as there is usually a delay while predators and parasites build up their numbers. For example, when 25% or more of seedlings are damaged by webworm, bare or very sparse patches in the crop will result. The crop should then be sprayed quickly as complete recovery is possible. An alternative, in grassy paddocks sown with reduced tillage where the risk is high, is to apply the insecticide with the knockdown herbicide.

Resowing after pests have progressed to a non-damaging stage is sometimes a viable option given an early break to the season. For example, cockchafers are major pests in the larval stage but insignificant once they have turned into pupae.

Changes in the weather can sometimes effect pest outbreaks e.g. warm-moist conditions can increase the incidence of a fungus that attacks aphids.

MAJOR PESTS

Some of the more important pests of wheat in Western Australia and they way they damage crops are described below.

Redlegged earth mite

Damage

Large numbers of redlegged earth mite (RLEM) are commonly found but normally do not affect cereals severely. Mites rupture cells on the surface of leaves and feed on exuding sap; affected leaves look silvered, but do not have holes or windows as with lucerne flea attack. Mite damage to seedlings is more severe if plant growth is slowed by cold and/or waterlogging.

Description

Adult mites *(Halotydeus destructor)* are about the size of a pinhead (up to 1mm). They have velvety black bodies and eight bright orange-red legs. The mites are often gregarious and are found clumped together in large numbers. They disperse quickly when disturbed.

Life cycle

Mites hatch from over-summering eggs in autumn when adequate moisture and low temperatures occur. Eggs produced through the season are thin-walled and hatch immediately, and several generations may develop over winter and spring. As pastures begin to senesce, the mites produce thick-walled eggs which resist drying over summer and carry the mite through to the next season.

Figure 11.1: Redlegged earth mite

Control

Pasture paddocks being prepared for cropping should have mites controlled the spring before the crop year. Treating seed with a systemic insecticide before sowing crops will protect seedlings from RLEM. Systemic chemicals can also be used if more than 60% of plants have emerged. If few plants have come up and cotyledons are being damaged as they emerge, it is more effective to use a contact insecticide. Mite control in dense spring pastures may require higher rates of insecticide than are effective on seedlings in autumn. Hard spring grazing will also reduce damage.

There are a number of organophosphorus-based chemicals currently registered for control of redlegged earthmite. These include chlorpyrifos, dimethoate, endosulfan and maldison, methidathion, omethoate phosmet, as well as the synthetic pyrethroids alpha-cypermethrin and bifenthrin.

Biological control of RLEM is being promoted by collecting a predatory mite, the anystis mite, from original CSIRO establishment sites and spreading it throughout the agricultural region. Establishing this predator depends on careful handling during collection and transport, and on ensuring there are areas of adequate dry plant cover in paddocks for shelter over summer.

MAJOR PESTS *(continued)*

Webworm

Damage

Large areas of emerging wheat crops may be destroyed by the continual chewing damage of a heavy webworm infestation. The caterpillars sever leaves or whole plants which they scatter on the ground or pull into holes near the plants.

Figure 11.2 Webworm larvae

Description

Webworm caterpillars *(Hednota* spp.) are seldom seen as they come above ground level only when conditions are cool and damp, and usually at night.

They may be located in their weblined tunnels from which plant parts may be seen protruding.

The caterpillars are pale to deep brown with a tinge of the green gut contents showing through. The head appears black or dark brown. Fully grown caterpillars are about 15mm long.

Life cycle

Caterpillars hatch from eggs laid amongst grass in autumn and feed throughout the winter.

Spring and summer are passed in the tunnels as resting stage caterpillars. After this, the insects proceed through the pupal stage and emerge as adult moths, which are about 10mm long and may be seen flying in large numbers on autumn nights. By day they hide in dry grass, the colour of which they closely resemble.

Figure 11.3: Webworm adults

Control

The paddock condition and the weather in autumn are very important in determining webworm numbers.

Eggs will not be laid in great numbers and will not survive well in a bare paddock or in stubble. Grassy situations favour survival.

Cultivations leading to a weed free paddock over a three week period destroy the young stages but reduced tillage cropping methods allow a greater survival. Hot and dry conditions during May and June, resulting in a lack of feed, could destroy most webworms.

If a quarter of the plants are being seriously damaged at or just after emergence, spraying should not be delayed as the continued feeding will kill many plants and result in bare ground or thin areas.

The only organophosphorus-based chemical registered for webworm control in cereals is chlorpyrifos. There are three synthetic pyrethroid chemicals; beta-cyfluthrin, alpha-cypermethrin and deltamethrin.

■ MAJOR PESTS *(continued)*

Lucerne flea

Damage

Wheat crops may be seriously retarded by the lucerne flea and seedlings may be killed in heavy infestations. Green leaf tissues are often eaten, leaving a surface of the leaf as a whitish film. Severely affected areas appear, from a distance, to be bleached.

Description

Lucerne fleas *(Sminthurus viridis)* usually spring from the plants when approached, using a special organ situated underneath the body. The lucerne flea is a dumpy looking and wingless creature of varied colour, but the larger specimens of 2 to 4 mm are predominantly green or yellow.

Life cycle

The first soaking autumn rains cause the special over-summering egg batches to hatch. Several generations may then develop over the growing period depending upon the weather. Eggs are laid in the soil and usually hatch in a few days. With the onset of warm and dry conditions in spring, the resting stage eggs (which are able to withstand summer conditions) are laid.

Control

The lucerne flea is favoured by heavy soils and cannot live in very sandy situations. It also depends on plentiful moisture.

Systemic or contact insecticides can be used as discussed for redlegged earth mite. Synthetic pyrethroid chemicals are unsuitable because they selectively kill redlegged earth mite which compete with lucerne flea. This can result in an increase in lucerne flea numbers after a synthetic pyrethroid treatment.

A predatory mite, the bdellodes mite, is present over most of the area occupied by lucerne flea and exerts a useful level of control. Another predatory mite, the neomolgus mite, was introduced by the CSIRO and has been released at many places in the agricultural area. It will extend the area and level of biological control.

Chlorpyrifos, dimethoate, maldison, methidathion and phosmet are the only chemicals registered for control of lucerne flea in cereals. These chemicals are all organophosphorus-based.

MAJOR PESTS *(continued)*

Cutworm

Damage

The cutworm chews through plant parts, often felling the plant at ground level. Just two or three large caterpillars would seriously damage a square metre of crop. This is not a regular pest but large areas may be affected.

Description

There are several species in this State, including *Agrotis infusa* and *A. munda*, which vary in appearance but the larvae are all smooth and plump.

Figure 11.4:Lucerne Flea

The larva of the most common species, the pink cutworm, is grey-green with a pink tinge and is usually found in sandy soils.

The larva of another common species, the bogong moth, is dark grey.

The larvae usually hide by day but may be found under the surface and often close to a damaged plant. They curl up when disturbed.

At times, brown cutworms (with a herringbone pattern along the back) damage crops. In south coastal areas they are more likely to be found on the soil surface by day, than are the pink or black cutworm.

Figure 11.5: Cutworm larvae

Figure 11.6: Cutworm adults

The adult moths of herringbone cutworm are of various species, and range from black, through grey to brown.

Occasionally, autumn attack by armyworm in cereals resembles cutworm damage (see armyworm). This is significant, because armyworm are harder to kill with insecticides than are cutworm.

Organophosphate, carbamate and pyrethroid chemical are all registered for control of cutworm in cereals. These include chlorpyrifos, diazinon, trichlorfon (OP), carbaryl (C) and alpha-cypermethrin, deltamethrin, esfenvalerate, lambda-cyhalothrin, permethrin, beta-cyfluthrin (SP).

Life cycle

Eggs are laid on the soil or on plant material close to the ground. The larva may grow 50mm long before becoming a pupa and then the adult moth. The adults are stout-bodied, with a wing span of up to 40mm. The forewings are patterned brown or dark grey. Several generations are possible in one season.

Control

The weather and food supply are the most important factors in determining abundance. Paddocks with good management of grasses during the previous spring are less at risk. Biological control, such as by fungal diseases, may be spectacularly successful, while wasp and fly parasites are also very active in preventing more frequent and serious outbreaks.

■ MAJOR PESTS *(continued)*

Desiantha weevil

Damage

Desiantha weevil (*Desiantha diversipes*) is a sporadic pest of cereal seedlings in southern areas. It is the larval stage which can completely destroy hundreds of hectares by feeding on underground parts of the seedlings. Plant growth may be slowed or plants may wilt and die and are easily pulled from the soil.

Figure 11.7: Desiantha weevil larvae

Description

The larvae are white, legless creatures 6mm long and with orange-brown heads. They remain under the soil and are difficult to locate although some painstaking digging may reveal the larvae close to plants.

Life cycle

Eggs are laid in autumn and hatch after opening rains and the larvae commence feeding on young pasture seedlings. When cereal crops are planted into heavily infested paddocks, they are attacked by the larvae which may be well grown. In spring the larvae pupate and become adults, which are grey-black weevils, approximately 5mm long with the typical weevil snout. The adults are common in spring and summer hiding under wood or stones or they may be found on cereal heads and can be harvested with the grain.

Figure 11.8: Desiantha weevil adult

Control

Chemical control after planting is not possible. Problem infestations are most likely to occur where shallow sand occurs over gravel or clay. As larvae will be larger following summer rain, crops should be planted early and shallow to minimise attack. Where the pest is confirmed, planting with treated seed at 90 kg/ha is recommended. Chlorpyrifos is the only chemical registered for control of desiantha in cereals.

MAJOR PESTS *(continued)*

Cockchafers

Damage

Cockchafer larvae feed underground and some species are serious pests which may slow growth or kill large areas of cereals by eating plant roots. Young plants without extensive root systems are worst affected and more than three grubs per shovel full of soil will cause some damage while five or more may completely destroy the crop causing erosion problems in the subsequent summer. The adult beetles are also destructive as they feed on tree foliage. The cockchafer which has caused the most damage to wheat crops in Western Australia is Heteronyx obesus.

Figure 11.9: Cockchafer larvae

Description

There are several important pest species and adults range in size from 5 to 20mm. Adults are usually brown or blackish beetles sometimes called “Christmas beetles”. The beetles fly readily and are attracted to lights. Cockchafer larvae are characteristically “C” shaped creamy white grubs between 2 and 25mm long.

Life cycle

The complete life cycle may take one or two years. Some species have a long larval stage which extends over 12 to 18 months. In most species the larva is active during late autumn and winter, then pupate in spring with adults emerging in early summer. Feeding, mating and egglaying may occur throughout summer.

Control

Control of cockchafer larvae is usually not economical. The main pest species in this State cannot be controlled with chemicals after planting as the larvae remain underground. It is not possible for insecticides to penetrate the soil far enough to have any effect; even following heavy rainfall. Shallow planting and planting with treated seed at a high rate may help to overcome the problem by establishing a strong root system early in the season. The problem is most serious when early growth is slow. Large populations of non-pest species may be present under

Figure 11.10: Cockchafer adult

young crops and in pasture without causing visible damage. The organophosphate chlorpyrifos is registered for cockchafer control in cereals.

■ MAJOR PESTS *(continued)*

False wireworm

Damage

False wireworm larvae may be present in the soil in high numbers with little or no damage to plant seedlings because they are primarily feeding on dead organic matter. Occasionally, larvae do chew into the seedling stem and roots, weakening the plant or ring barking the stem and causing the plant to fall over. Strong winds, which buffet young fragile seedlings, increase the level of plant deaths. In swathed crops adult beetles may cause a problem through contamination of grain samples, as adults shelter within the swath and are then caught up into the harvester.

Description

False wireworm is a general description given to several species of soil dwelling beetle larvae belonging to the family Tenebrionidae. They are primarily scavengers, feeding on fungi and dead plant material. The larval or worm stage of the beetle's life cycle has been responsible for attacking some seedling crops. Two main species are known to cause damage in Western Australia: the Vegetable beetle (*Gonocephalum elderi*) and the bronze field beetle (*Adelium brevicorne*).

Figure 11.11: Bronze field beetle

Control

Increased stubble retention and use of minimum tillage, allowing an abundance of plant material on the surface, favours beetle survival and increase. False wireworms are not a regular pest of cereal crops and use of chemical control is often uneconomical. As it is difficult to anticipate false wireworm damage, the best option may be to observe the crop carefully and replant the affected parts of the paddock if necessary.

The organophosphate Chlorpyrifos is the only chemical registered for control of false wireworm in cereals.

MAJOR PESTS *(continued)*

Aphids

Damage

Aphids affect cereals by direct feeding on plants, and/or by transmitting barley yellow dwarf virus (BYDV).

Direct damage by aphids feeding can cause losses of up to 30% where crop yield potential is 3 t/ha and higher. Damaging populations may develop in three out of five years. Direct damage occurs when colonies of 10 to 100 aphids develop on stems, leaves and heads, from seedling stage through to head filling. The degree of damage depends on the growth stage of the crop, percentage of tillers infested, aphids per tiller, and the duration of the infestation. Feeding damage often has no obvious signs or symptoms, although heavily infested plants may be covered in black sooty moulds which live on the sugary honeydew excreted by aphids.

BYDV is introduced into cereal crops from infected grasses by flying cereal aphid vectors. The aphids carry the virus in their mouthparts. Medium to high rainfall zones, where aphids can arrive early in the life of the crop, are at most risk. Virus symptoms take at least three weeks to appear and can easily be confused with those of nutrient deficiencies, e.g. leaf yellowing in barley and some wheat varieties, reddening of older leaves in oats and the flag leaf in other wheat varieties. Damage is greatest when spread occurs early in the growing season, before the end of tillering. Plants become stunted and yield losses can be up to 50%. Also grain quality can be affected as the proportion of shrivelled grain increases.

Description

Corn aphid *(Rhopalosiphum maidis)* and wheat/oat aphid (R. padi) cause most yield loss. Rice root aphid *(R. rufiabdominalis)* and Sitobion miscanthi (no common name) are also found in cereals but usually in lower numbers. Wingless aphids are about 0.2 to 2.5mm long.

Corn aphids are dark blue-green to grey-green, often with a white dusty appearance. Colonies are often difficult to detect because they usually develop within the furled leaves of tillers any time from seedling to head emergence. Barley is more likely to be affected than wheat.

Wheat/oat aphids are the most abundant species of cereal aphids and vary from mottled yellow-green through olive-green and dusky brown, to a blackish green, and are characterised by a reddish patch on the tip of the abdomen. Colonies develop on the outside of tillers from the base upwards on stems, nodes and backs of mature leaves, starting any time between seedling stage and grain filling. Heavy infestations can blacken heads and flag leaves, and these are the aphids most commonly reported by farmers. Wheat/oat aphids are more mobile than corn aphids, and can drop to the soil and crawl to other plants. They cause yields losses probably by reducing grain weight and grains per head. They can also be important in spreading BYDV.

Figure 11.12: Wheat/Oat aphids

Rice root aphids are like wheat/oat aphids, but can also infest plant roots. They have a reddish patch in the middle of the back, and are most likely to be found in drier agricultural areas. S. miscanthi aphids are light green with yellow-green tinges, usually found in spring, without developing large colonies.

Rose-grain aphids are potentially serious pests, but are yet to enter Western Australia from the eastern States where they are widespread. They are green spindle-shaped aphids attacking wheat and barley during grain filling.

Life cycle

Winged aphids fly into crops from pasture grasses or other crops, and start colonies of wingless aphids. All aphids in a cereal crop are females, able to give birth to live young without the need to mate. Reproduction is rapid when weather conditions are favourable, leading to population outbreaks. Cold conditions slow the rate of development. When plants become unsuitable or overcrowding occurs, winged young are produced which migrate to other plants or crops.

Control

For BYDV control see the Leaf Diseases section.

Crops should be checked from late tillering onwards for corn aphids in the furled growing tips, and for wheat/oat aphids on stems, backs of leaves and ears.

Crops expected to yield 3 tonnes/ha or more are most at risk.

Spraying is worthwhile if 50 per cent of tillers have at least 10 to 20 aphids. Mixed infestations of both aphid species may cause more damage than either species on its own.

Crops sprayed before Zadok's stage 30 may need respraying at Zadok's stage 50 or later, if aphid numbers build up again.

Parasitic wasps, ladybirds, lacewing and hoverfly larvae can provide useful biological control, mainly by preventing secondary outbreaks. The use of 'soft' insecticides that only kill aphids is advocated. When aphid densities are high weather warm and moist, certain fungi may kill a large proportion of the population.

Carbamate pirimicarb and the chloronicotinyl imidacloprid, are both registered for aphid control in cereals in Western Australia as well as the organophosphate chlorpyrifos.

Armyworm

Damage

Armyworms are regular pests of coarse grain crops on the south coast of Western Australia and occasional pests in inland areas. Towards the end of spring, when crops are approaching maturity, large armyworm caterpillars chew through the stems of barley just below the head, causing heads to fall to the ground. If in large numbers early in the season, armyworms may eat leaves and be confused with cutworm.

Description

There are four species of armyworm in Western Australia – the common armyworm, the southern armyworm, the inland armyworm and the sugarcane armyworm (*Mythimna convecta, Persectania ewingii, Persectania dyscrita and Mythimna loreyimima* respectively). Of these, the common armyworm is the most damaging. Moths are stout bodied, grey to cream, with a wingspan of about 40mm. They fly at night and are strongly attracted to lights. Armyworm caterpillars vary in colour depending on their numbers in a crop. If there are many caterpillars in a crop they become dark, while if the population is low, the caterpillars are much paler. Armyworms are about 40mm long when fully grown and can be distinguished from cutworms and budworms by their large heads and three prominent white stripes on the "collar" behind the head. Often the armyworms themselves will not be seen as they feed mainly at night, but their droppings (which look like small green "square" hay bales) will be obvious on the ground below the crop canopy. Another indicator that armyworms are present is damage to ryegrass seed heads.

Figure 11.13: Armyworm larvae

Life cycle

Armyworms have three or four generations per year and on the south coast they survive over summer on self-sown cereals and grasses that germinate with summer rains. Numbers can increase rapidly in years with heavy summer rain. In spring it takes about three weeks from when the eggs are laid for them to hatch and for the caterpillars to reach head-lopping size. Once damage begins many heads can be lopped in a short time. Inland armyworm breed up in pastoral areas during wet summers giving rise to large flights of moths which can invade agricultural areas.

Figure 11.14: Armyworm adult

Control

Heatwaves may kill most of the caterpillars and native parasites can exercise good control, meaning that spraying is not normally required every year. Several introduced wasp parasites including Apanteles ruficrus have been released to increase biological control.

The organophosphates chlorpyrifos, diazinon, maldison, methidathion, trichlorfon; the carbamates methomyl and carbaryl as well as the synthetic pyrethroids alpha-cypermethrin, beta-cyfluthrin, cypermethrin and deltamethrin are all registered for armyworm control.

Stored Grain Insects

Damage

Once grain reaches storage its quality cannot go any higher, all the grower's effort and expense is now held in one place and its value can only go down unless the grain is protected. Grain stored on farms will eventually become infested by grain beetles or moths unless specific measures are taken. Primary grain insects found in Australia are those which can attack and reproduce in whole grain and include the lesser grain borer, the granary weevil and the rice weevil

Figure 11.15: Lesser grain borer

(*Rhyzopertha dominica*, *Sitophilus granarius* and *Sitophilus oryzae* respectively). Secondary grain insects require grain which is cracked or has been damaged by primary insects. The rust-red and confused flour beetles (*Tribolium castaneum* and *Tribolium confusum*), sawtoothed grain beetle (*Oryzaephilus surinamensis*) and flat grain beetle (*Cryptolestes spp*) are secondary insects. All the grain moths with the exception of the Angoumois grain moth (*Sitotroga cerealella*) are secondary insects. Heavy infestations can taint grain and reduce germination of seed. It is, however, their contamination of export grain which is the major problem. No grain insects whatsoever are permitted in grain shipments and this position is vigorously defended by inspection and fumigation. Grain and feed merchants in Western Australia have agreed that they will no longer accept infested grain.

Figure 11.16: Rice Weevil

Description

All stored grain beetles are small, 2 – 5 mm long and brown to black. True weevils can be identified by their elongated snout used to bore into seeds for egg laying. The larvae of the grain moths are generally pinkish or cream and may produce webs across the surface of the grain.

Pests of quarantine significance include the warehouse beetle (recently found in Western Australia) and the khapra beetle. The latter is the most serious pest of stored grain in the world and is not found in Australia. The khapra beetle is almost impossible to distinguish from the warehouse beetle and a wide variety of native Trogoderma beetles found in Western Australia, hence the need for monitoring and surveillance.

Life cycle

The eggs of secondary beetles are laid free between grains or in the cereal product. The larvae also live externally to the grains and pupate free in the commodity. The lesser grain borer lays its eggs free in the grain, but the larva enters a grain shortly after hatching and completes its life cycle inside the grain. The adult bores its way out of the hollowed out grain upon emerging from the pupa. The whole life cycle of stored grain pests is usually spent inside the grain bulk. Under ideal conditions (around 28°C) the life cycle may be completed in 30 to 40 days but temperatures below 15°C may extend this to 300 days. The confused flour beetle and granary weevil are both flightless while the others are strong fliers.

Figure 11.17: Khapra beetle larva

Control

Grain insects are declared under the Agriculture and Related Resources Protection Act. Limited chemical controls are available to Western Australian farmers due to the State's residue-free approach to grain storage and marketing. Because no stored grain pests can exist in

MAJOR PESTS *(continued)*

standing crops, emphasis is placed on hygienic storage and rigorous cleaning of handling equipment.

Stored grain can be protected from subsequent infestation with diatomaceous earth protectants like Dryacide®. Existing infestations are best treated with the fumigant phosphine used in sealed storages. These storages should be tested annually to ensure they remain gas-tight and failed rubber seals replaced. Ineffective use of phosphine can lead to resistance and eventually control failures. In-transit fumigations are illegal and extremely dangerous.

Figure 11.18: Rust-red flour beetle

Phoscard® farm fumigation indicator cards have been developed by Agriculture Western Australia to assist farmers in assessing the success of their phosphine fumigations. Sample Phoscards are available from AGWEST.

CHAPTER TWELVE

WEED CONTROL IN WHEAT

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Introduction

David Bowran

Weeds often impose the most significant costs to wheat crops, either from the yield loss which comes from competition between the crop and weeds, or else in the costs of applying appropriate control measures. While herbicides provide effective tools to manage weeds in many crops, the changes in weed spectrum that have occurred with herbicide resistance and the development of new cropping systems should remind us that weeds will exploit any opportunities become available within the crop.

When developing a weed control program for use in wheat it is vital to plan ahead so that all management techniques which minimise the build up of weeds in phases prior to the wheat crop can be considered or used. It is also important to know the weed species present, their density, area involved and distribution over the paddock. Different weed species have different competitive abilities and the economic threshold for control varies between weed species.

The acceptable threshold of weed numbers is lower in a continuous cereal-lupin rotation than in a cereal-pasture rotation. In a continuously cropped paddock, control of early weed competition and prevention of seed set from late germinated weeds are both important. When a cereal crop is followed by pasture, emphasis should be placed on reducing early weed competition rather than preventing seed set, as weeds which germinate later in the crop are less competitive and their seed production may be necessary for pasture establishment.

COST OF WEEDS IN WHEAT

In cereal crops, the potential yield is determined by the number of tillers per plant, the number of grains per head and the grain weight. Competition for nutrients is critical in determining the first two factors (with nitrogen being the nutrient most in demand by the crop and weed) and usually occurs in the first two to five weeks after crop emergence, while grain weight is determined after anthesis and is mostly affected by competition for water during grain filling.

To gain the full yield response to weed control it is therefore critical that weed competition be eliminated as early as possible in crop development. This loss is a function of weed density, as lower weed densities will remove less nutrients and may even be out-competed by the crop. At higher densities, or where transplanted weeds are present, delays may be costly. Trial evidence suggests that where grass weeds such as wild oats or brome grass are present at similar densities to the wheat crop, yield losses of 15-25kg/ha/day may occur and that removal in the first five weeks after emergence (or before emergence if a residual herbicide is used) is required. It may well pay to change management practices to avoid loss, especially if weather or other factors will cause significant delays in controlling the weeds.

Just how much a weed will reduce crop yield is a function of the species, the density of weeds, the density of the crop, when the weed emerges relative to crop, and when the weed is removed from the crop. Table 12.1 shows the average yield loss from a number of different grass species in wheat crops when the weed emerges with the crop (Poole and Gill, 1987).

It can be seen from Table 12.1 that weeds can produce severe reductions in yield even at quite low densities. Where a farmer establishes wheat at 125 – 150 plants/m2 and a weed such as ryegrass emerges at the same density, then the potential yield foregone is about 25%. If this weed cannot be selectively removed with herbicides, then this yield is unlikely to be recovered. Fertilizer applied to the crop not only enhances crop yield but also promotes weed growth and seed production, and is often lost to that years crop. Increasing crop density has a major effect on reducing these competition factors. Where weed density is low, increasing crop density will be a major factor in reducing competition from weeds and limiting weed seed production for a following crop.

Weeds may impose other costs in wheat production. Weed seed contamination which reduces grain quality can be significant if a lower premium is obtained or the crop has to be cleaned after harvest. Weed seeds which have the potential to be toxic pose particular problems as they may be difficult to identify or to clean from the crop e.g., drake (*Lolium temulentum*).

Table 12.1 – Yield loss (%) with increasing density of grass weeds in wheat (normal seeding rate 50-60 kg/ha)

Weed density(plants/m^2)	Annual ryegrass	Wild oats	Brome grass	Barley grass
25	6	11	9	7
50	11	20	17	13
100	20	34	31	24
150	28	43	42	33
200	34	50	50	42
300	44	58	62	53

WEED CONTROL BEFORE SEEDING

Weed control for the wheat crop must start as soon as winter active weeds germinate in summer or autumn. In most cases, herbicides if applied while the weeds are small, provide the most cost effective solution to this problem, while conserving the maximum soil moisture for crop establishment. Glyphosate based herbicides provide a wide spectrum of weed control, can be tank mixed with other herbicides for enhanced knockdown of weeds that are hard to kill and are relatively low cost. The bipyridyl herbicides paraquat and diquat also offer excellent knockdown weed control especially where weeds are small. The double knock system of using glyphosate followed by bipyridyls 5-10 days later provides faster burndown of weeds prior to seeding and provides improved control of weeds which are hard to kill with glyphosate.

Cultivation is a useful tool where weed germination is early and drying conditions follow. Cultivation, to a maximum of 2.5cm, can stimulate weed seeds in the seedbank to germinate on subsequent rain (autumn tickle), and these can then be killed with knockdown herbicide or further cultivation. Cultivation is a useful tool for some weeds which are hard to kill with knockdown herbicide such as mallow and Vulpia (silvergrass).

Early grazing can be an extremely valuable tool for reducing weeds and minimising the amount of herbicide required to kill weeds prior to seeding. Animals also consume weeds such as wireweed and melons and so reduce the blockages in seeding machinery.

Burning of stubble kills both weed seeds and germinated weeds, and where wheat is sown after wheat will assist in leaf disease control. Where weed seeds have been concentrated into header trails it may be possible to kill 80% of seeds prior to opening rains if the stubble is ungrazed and a hot burn can be achieved.

■ HERBICIDES FOR WEED CONTROL IN WHEAT

Herbicides are now the tool of choice for selective weed control in wheat and the range of options for most weeds is extensive. This section brings up to date the chapter on herbicides for weed control in wheat in the publication "The Management of Agricultural Weeds in Western Australia" (1993).

Pre-emergence weed control

Barley grass, brome grass and Vulpia spp (silvergrass)

Vulpia, brome grass and barley grass are often a problem in emerging crops after early seeding or with crops planted hastily on the first or second rains. Options for control include;

- delayed seeding and use of knockdown,
- shallow cultivation – tickle.

Of the pre-emergence herbicides sulfosulfuron can provide good control of all species, while metribuzin + trifluralin can be used for brome grass control in Blade wheat. Most of the other pre-emergence herbicides do not give satisfactory control of these grasses, though the trifluralin + oryzalin combination does provide good control of Vulpia in many cases. Diuron applied immediately after seeding can give good control of Vulpia.

Barley and brome grass have been successfully removed from wheat as they emerge, using low rates of paraquat. Timing is critical, and wheat should not have more than half the first leaf emerged. Spraying under sunny conditions stops paraquat translocation to the rest of the emerging seedling and minimises damage. However, the crop will need to be re-sown if the technique fails.

Annual ryegrass and wild oats

Pre-emergence herbicide options for the control of ryegrass include trifluralin, pendimethalin, trifluralin + oryzalin, chlorsulfuron and triasulfuron. Where ryegrass and wild oats occur together trifluralin + triallate may be used, but where wild oats occur alone, triallate is the preferred option.

Efficacy with these herbicides can be variable due to the requirement for incorporation or, on sandy soils, the high leaching of chlorsulfuron and triasulfuron. Many farmers have switched to post-emergence herbicides such as diclofop methyl and tralkoxydim for these reasons for the control of ryegrass and wild oats. Many farmers who originally used trifluralin switched to chlorsulfuron or triasulfuron because these herbicides control a wide range of broad-leaved weeds as well as ryegrass.

With the development of resistance to diclofop methyl and the sulfonyl ureas in ryegrass populations, there has been a large increase in trifluralin use for the control of ryegrass.

Broad leaf weeds

Chlorsulfuron and triasulfuron provide good control of a wide range of broad leaf weeds such as capeweed, doublegee, wireweed, dock, cape tulip, wild turnip, wild mustard and soursob. Triasulfuron may provide up to 70% control of wild radish with pre-emergence application.

Diuron applied immediately after seeding has good activity on capeweed, crassula and toadrush. Transplant capeweed can be successfully treated with diuron + clopyralid and if used just prior to crop emergence yield reductions from large transplants can be largely overcome.

Pre-emergent Herbicide Overview

This section provides an overview of the herbicides that are incorporated before or during seeding, or which may be applied after seeding but before crop emergence.

Group D

1.Trifluralin

The advantages of trifluralin are that it is a relatively cheap pre-emergence herbicide that can be tank-mixed with knock down herbicides. Points to note:

- Trifluralin is slightly volatile and co-distills with water vapour, and should be incorporated in the soil within 4 hours if applied to wet soil. Losses due to volatilization are greatest with moist soil and warm temperatures.
- Traditional ways of using trifluralin required paddocks to either be pre-worked or have stubble residues that did not cover more than 25% of the soil surface. Excessive amounts of stubble can make good incorporation very difficult, if not impossible, unless culti-trash seeders are used. Recent innovations with no-till seeding show that if trifluralin is applied prior to seeding then knife points can throw sufficient soil to cover the trifluralin and prevent volatilisation. If ryegrass seed is on the soil surface sufficient trifluralin is applied to the soil and seed to prevent germination.
- Trifluralin must be incorporated evenly in the top 2.5 cm of soil with wheat sown 1cm under the trifluralin layer when using full cut points. Wheat sown in the trifluralin layer will either fail to emerge or if it emerges it may have stunted root systems and poor subsequent growth. This factor makes it important to consider the type of seeding equipment used and the coleoptile length of the wheat variety. As a safety margin it is wise to suggest a 10% increase in seeding rates if trifluralin is used. With no-till and knife points the thrown soil acts as the incorporation layer, but soil in the furrow will be free of trifluralin and prone to weed germination.
- As an alternative to incorporation by sowing, trifluralin can be applied immediately after sowing and incorporated by prickle harrows such as Phoenix harrows. This will leave a very uniform, shallow layer of herbicide, but losses by volatilization will be greater than with a full incorporation.

Trifluralin is registered for application and incorporation one or two weeks before sowing. However,

■ HERBICIDES FOR WEED CONTROL IN WHEAT *(continued)*

many farmers have successfully incorporated trifluralin by sowing, by maintaining good depth control and adequate seeding rates.

The level of control of ryegrass will vary but, generally speaking, 75% control should be expected. This makes trifluralin an option where ryegrass densities are likely to be low to medium. Some farmers achieve better results with knife points but only if ryegrass seed is on the soil surface.

2. Trifluralin + oryzalin

The two dinitroaniline herbicides, trifluralin and oryzalin are combined together in one herbicide product. Unlike trifluralin, oryzalin is not volatile but because the trifluralin is present the mixture must be treated in the same way as other trifluralin based products.

3. Pendimethalin.

Like oryzalin it has lower volatility and water solubility than trifluralin. Consequently it is important to achieve uniform incorporation in the top 2.5cm of soil if good weed control is to be achieved. Like trifluralin, crop damage will occur if seed is sown into the treated band.

Group E
Triallate

The development of diclofop resistance in wild oats has resulted in renewed interest in triallate. In the past, farmers have been put off using triallate because of the soil incorporation requirements. According to the existing label, triallate must be harrowed into the soil immediately after application. However, many farmers around Australia have been getting good results with triallate without strictly following the incorporation instructions. The following characteristics of tri-allate, may explain why this is so:

- tri-allate does not volatilise readily and is not broken down by sunlight;
- the response to incorporation is due to the need for moist soil to activate tri-allate;
- tri-allate is bound onto soil particles and is stable to volatilization from dry soil for up to 28 days at temperatures of up to 50°C.

On application to soil, tri-allate becomes bound to soil colloids and vaporises in the presence of water. It is active in a soil moisture range from 5% above permanent wilting point to 5% below field capacity. The only significant losses are likely to occur from a moist soil surface.

Losses of triallate from a dry soil surface are expected to be low and a delay in incorporation of up to 24 hours is unlikely to significantly reduce herbicide activity. This will enable more flexibility in the seeding operation. The only significant losses are likely to occur from a moist soil surface.

A maximum of 25% ground cover of crop residues can be tolerated. Rain will wash triallate off stubble onto soil.

Triallate can also provide a moderate level of control of annual ryegrass and where both ryegrass and wild oats are present a mixture of trifluralin + triallate can provide good control of both weeds.

Group B
1. Chlorsulfuron and triasulfuron

These are pre-emergence herbicides suitable for the control of ryegrass and a wide range of broad-leaved weeds. After its introduction in 1982, chlorsulfuron was rapidly adopted because of its ease of use and broad-spectrum weed control.

These herbicides should be applied as near to seeding as possible, application rates should not be cut if conditions are warm and the herbicides should not be left in the tank but should be sprayed out immediately. These herbicides should not be used on sensitive wheat cultivars, especially if temperatures are low.

Precautions which need to be taken when using sulfonyl ureas are as follows.

- They should not be used on paddocks where waterlogging, extreme alkalinity or extreme acidity are likely because crop stress can reduce the ability of wheat plants to metabolize the herbicide, thus leading to crop damage. Herbicide tolerance results show that recovery is often faster from triasulfuron retardation, but final yields for both herbicides are often similar
- Chlorsulfuron and triasulfuron as root pruning herbicides, can induce trace element deficiencies in crops where the trace element levels in the soil are deficient or marginal.
- Some varieties of wheat and barley have lower levels of tolerance to the sulfonyl ureas. Neither herbicide should be used pre-emergence in oats.
- Sulfonyl urea residues in the soil after cereal crops can damage a subsequent legume crop if conditions remain dry in the year of application or if the soil is alkaline.

2. Sulfosulfuron

Unlike the previous two sulfonyl ureas, this recent introduction has activity on wild oats, brome grass and barley grass. This makes the herbicide a useful addition to the tools available for brome and barley grass, and while strong suppression is seen in many cases, excellent yield responses can occur due to reduced weed growth. The herbicide is useful for barley control in wheat.

Group C
1. Metribuzin

When combined with trifluralin, metribuzin can provide good control of brome grass and annual ryegrass in Blade wheat. Most wheat varieties show some sensitivity to this combination with 20% yield losses recorded in tolerance screens on sandy soils. Heavy rain can leach metribuzin on sandy soils and seriously reduce efficacy. Metribuzin may provide control of broad leaf weeds in situations where rain is light after incorporation.

■ HERBICIDES FOR WEED CONTROL IN WHEAT *(continued)*

2. Diuron

Vulpia control is often excellent when diuron is applied to moist soil immediately after seeding. Heavy rain can wash diuron into furrows and kill wheat, so it has to be applied to either a level seed bed with conventional sowing, or else applied before sowing in no-till systems. Heavy rain may wash diuron into furrows in no-till seeding systems.

Early post-emergence weed control

(crop emergence to pseudo-stem elongation)

In considering early post-emergence treatments to any crop it is important to bear in mind many of the points such as those relating to timeliness of application, rate of herbicide and crop effects. Herbicides are available for most weeds for in-crop weed control unless herbicide resistance has developed.

Grass Weeds

Barley, brome and silver grasses: Of the grasses found growing in cereal crops, brome grass, barley grass and silver grass have often been the hardest weeds to control, but the new sulfonyl urea herbicide sulfosulfuron has allowed selective control in wheat. Like other sulfonyl ureas, plants may be strongly suppressed by the herbicide and then outcompeted by the crop. It is unclear yet as to whether or not all Vulpia species are controlled by sulfosulfuron.

Annual ryegrass and wild oats: Both annual ryegrass and wild oats are two of the most competitive weeds of cereal

Table 12.2 – Herbicides registered for the post-emergent control of grasses in wheat.

Weed	Herbicide	Timing (no. leaves)	Comments on Use
Annual ryegrass	diclofop-methyl	1-4	Most active herbicide for this weed in cereals
	chlorsulfuron	up to 3	Generally gives good control of small weeds but sometimes only provides suppression for 2-4 weeks.
	clodinafop	1-3	Generally weaker on ryegrass than wild oats
	tralkoxydim	1-3	Weakest herbicide available for annual ryegrass and is best used where wild oats is major weed.
Wild oats	diclofop-methyl	1-4	Less active on wild oats than on ryegrass. Tillered plants may be poorly controlled.
	fenoxaprop	2-7	Generally gives excellent wild oat control even on tillered plants.
	tralkoxydim	1-6	Excellent wild oat control on plants of most sizes.
	flamprop-ethyl	tillering	Generally applied later than other herbicides so yield responses may be smaller. May control wild oat resistant to other herbicides.
	clodinafop	1-4	Excellent wild oat control
	sulfosulfuron	1-4	Good control achievable, strong suppression common
Barley, brome grass	sulfosulfuron	1-4	Good control and strong suppression of these weeds. Severely stunted plants can remain.

■ HERBICIDES FOR WEED CONTROL IN WHEAT *(continued)*

crops. The conditions of cereal cropping favour their germination and vigorous growth, which when combined with their high seed populations from preceding crops or pasture, can often lead to very large reductions in potential yield. Both species exhibit staggered germination which often leads to very poor cultural control. Because of their strong competitive effect with the crop, it is desirable to control these weeds in the first few weeks after crop emergence if maximum benefit is to be obtained from the use of a post-emergence herbicide. The major herbicides for control of these two grasses are shown in Table 12.2.

Drake: Drake is a grass weed which looks very similar to annual ryegrass at the seedling stage, but can be identified at maturity by its larger ears and bigger seeds (which makes separation from the cereal grain difficult). Drake is an unwanted contaminant of grain because of its potential to carry ergot – a fungal structure – which can poison products made from the contaminated grain. Drake also tends to have a slower germination than ryegrass. The herbicides registered for ryegrass have all been found to work in glasshouse experiments. These are diclofop methyl, tralkoxydim and chlorsulfuron.

Canary grass: Canary grass is the only other grass weed which commonly infests wheat and is usually confined to heavier red clays and clay loams. While not common as a weed, in some situations it may be of sufficient density to justify control. The herbicides fenoxaprop and tralkoxydim are registered and provide good control. Diclofop methyl may give suppression if applied at the one leaf stage.

Broad-leaved weeds

The number of broad-leaved weeds found in crops is generally much larger than for grasses. However in general there are only a few which are sufficiently widespread or competitive to warrant a discussion. The more common broadleaf weeds will be discussed below. However some weeds are of significant local importance (soursob, sorrel, dock, fumitory, self sown legumes, wireweed, Paterson's Curse) and for these and less common weeds referral to the Cereal, Pea and Lupin Weed Spraying Charts will provide guidance to what herbicides can be used. Table 12.3 gives an indication of the herbicides used on the major broad-leaved weeds in W.A.

Capeweed: Capeweed is probably the most common broad leaf weed of cereal crops given its widespread occurrence in pastures and the relative ease with which its seeds can be wind blown between paddocks. Seedling capeweed in crop is readily controlled by a wide range of products with mixtures of diuron + MCPA and 2,4-D providing very cost effective control. Clopyralid is a very effective herbicide for capeweed for both seedlings and transplants. It is however slower acting than bromoxynil or diuron based mixtures but has advantages in excellent crop safety and in being compatible with most other broad leaf and grass weed herbicides. Terbutryne based herbicides are most effective on seedling capeweed but have the effect of causing crop yellowing in some situations. Transplant capeweed is a major problem in some seasons and is then a very competitive weed. Ideally the herbicide to use in these situations is one which combines a rapid knockdown effect with slower systemic activity. However, no herbicide currently does this although bromoxynil + MCPA and terbutryne +MCPA can come close. Maximum rates of clopyralid are generally very effective, while the addition of clopyralid to other herbicides can enhance their systemic activity.

Doublegee: Doublegee infestation of cereals is generally on a lesser scale than for capeweed, but its dormancy and staggered germination can pose problems with regard to optimum timing of application. Both metsulfuron and diuron + MCPA have proven to be cost effective herbicides for small seedling doublegee, with metsulfuron the herbicide of choice where large or transplanted doublegees occur. Dicamba based herbicides are an excellent alternative especially if rotational options do not allow a Group B herbicide in the cereal year. It is important to remember that seed production can begin at relatively early growth stages (as few as 4 leaves) especially on stressed or later emerging plants, and that if control aims to reduce seed production, delays in application to ensure adequate emergence may be counter-productive in some situations.

Wild Radish (and other wild crucifers): The wild crucifers, and wild radish in particular, continue to be some of the most widespread weeds of cereal crops despite 45 years of chemical control. Most weeds of this family exhibit strong dormancy and staggered germination characteristics which make their control difficult. While the sulfonyl urea herbicides (chlorsulfuron and triasulfuron) can provide some measure of pre-emergence control it is usual to require follow up treatment where these herbicides have been used. The phenoxy herbicides 2,4-D and MCPA have been widely used for wild radish control since the late 1940s, but because of the potential crop damage problems have taken a lesser role in more recent years as safer products with earlier application timings have been developed. Both sulfonyl ureas chlorsulfuron and triasulfuron have proven to be effective wild radish herbicides with good capacities to kill quite large plants when used in a late post-emergent role. Combinations of MCPA ester or amine with other herbicides (bromoxynil, diflufenican, diuron, terbutryne) are all generally effective if the wild crucifers are small but some consideration of application timing is usually necessary. Bromoxynil + diflufenican combines two effective wild radish herbicides which provides for good crop safety and so allows for earlier application than with the MCPA mixture herbicides. For best weed control with bromoxynil + diflufenican it is necessary to ensure that rates suit weed size. The current guidelines for herbicide rotation should be carefully considered when planning wild radish control as resistance in wild radish to Groups B, C, F and I is present in either Australia or overseas. The rotation is

■ HERBICIDES FOR WEED CONTROL IN WHEAT *(continued)*

especially important with diflufenican based products, as Brodal® remains the key herbicide for wild radish control in lupins.

Late post-emergence weed control

(pseudo stem elongation to grain maturity)

To avoid crop yield losses from competition, weeds must be controlled early in the season. However, weeds may appear late in the crop because of;

- late germination of weeds,
- failure of earlier herbicide treatments,
- lack of a control method.

It is important that these weeds are prevented from maturing and setting seeds within the crop.

Harvested grain that is contaminated by weed seeds and other plant fragments may be unmillable. Strict grain receival standards for levels of weed seed contamination and unmillable material have been defined by the grain marketing authority.

Weed seed contamination in grain can be reduced by improving the screening capacity of the header or by delaying harvest until weed seeds have been shed. These techniques allow large numbers of weed seeds to return to the soil and will make weed control more difficult in future crops. There is also a chance that seeds of herbicide resistant weeds will be returned to the field. Trailing bins behind the header have been designed to collect and remove weed seeds from the field.

The difference in price paid for Australian Standard White and General Purpose wheat may be sufficient to justify commercial seed cleaning to remove weed seed contaminants.

An integrated approach to weed control will ensure that low numbers of seeds are carried over from year to year. Thousands of seeds may be produced by a single plant. While a small infestation of weeds late in the season may not reduce grain yields, the weed seed bank may be dramatically increased. Weed seeds returned to the field may create a problem for many years, particularly when the seeds have a high level of dormancy.

Late post-emergence chemical control will reduce weed seed contamination of the harvested grain sample and reduce weed seed carryover into the following season.

The phenoxy herbicides (2,4-D and MCPA) are commonly applied as late post-emergence treatments and to reduce the seed set of wild radish, wild mustard, wild

Table 12.3 – Herbicides registered for the post-emergent control of the major broad leaf weeds in wheat crops in Western Australia.

Herbicide	Capeweed	Doublegee	Wild Radish
Bromoxynil	●	●	●
Bromoxynil+diflufenican	●	●	●
Bromoxynil+MCPAe	●	●	●
Bromoxynil+MCPAe+dicamba	●	●	●
Chlorsulfuron			●
Clopyralid	●		
Dicamba		●	
dicamba+(MCPAa or 2,4-Da)	●	●	●
Diflufenican+MCPAe	●		●
diuron+(MCPAa or 2,4-Da)	●	●	●
Flumetsulam			●
MCPA amine, ester	●		●
Metosulam			●
Metsulfuron		●	
Sulfosulfuron			●
Terbutryne+MCPAa	●	●	●
Triasulfuron			●
2,4-D amine, ester			●

MCPAa = amine form of MCPA, MCPAe = ester form of MCPA,

2,4-Da = amine form of 2,4-D, 2,4-D e = ester form of 2,4-D

■ HERBICIDES FOR WEED CONTROL IN WHEAT *(continued)*

turnip and lupins. These herbicides must be applied before booting and preferably no later than full flag leaf emergence otherwise serious yield losses may occur (these herbicides can stop pollen mother cells dividing and significantly reduce pollination of the crop). Sulfonyl urea herbicides such as triasulfuron can be applied more safely during booting and grain filling but wild radish resistance may limit the long term usefulness of such treatments. 2,4-D can be safely applied after soft dough, but radish control will be less effective. Combinations of 2,4-D ester and Ally® have caused large yield reductions and should not be used.

For wild oats a recent innovation is the application of Mataven® during stem elongation through to booting at lower rates than those necessary to kill wild oats. Such treatments act to prevent ear development and may be useful in preventing weed seed return to the seedbank.

The benefits of late post-emergence weed control are reductions in;

- weed seed contamination of the harvested grain sample,
- the need for seed cleaning,
- seed-set and seed carry-over,
- weed infestations in future crops.

INTEGRATED WEED MANAGEMENT

No one weed control method is normally sufficient by itself for an effective weed control program at reasonable cost. Instead, a combination of agronomic, biological and chemical methods will usually be found to be the most efficient and cost-effective. In recent years there has been a trend towards over-reliance on the use of selective herbicides for weed control at the expense of traditional cultural methods. The widespread onset of herbicide resistance has meant that selective control of annual ryegrass, wild oats and wild radish in wheat is now difficult for many farms and a whole farm integrated approach is necessary. For the wheat crop a number of options are available which can be employed to minimise the effects of weeds in the wheat crop.

- burning stubble and header trials to reduce weed seeds on the surface,
- light autumn cultivation to ensure even weed germination,
- non selective herbicides such as paraquat applied after seeding and just prior to crop emergence where the weeds have already germinated,
- Using knockdown rates of herbicides or cultivation treatments which kill all weeds prior to seeding,
- delayed sowing to ensure more weeds emerge prior to seeding,
- increased seeding rate (yield losses from weeds are minimised with sowing rates above 100kg/ha),
- closer row spacing (e.g. 3”. 7cm, broadcast) to ensure less space for weeds and more competition,
- placement of fertiliser below the seed or between twin rows of crop so that weeds are further from the nutrient,
- choosing varieties with the best agronomic adaptation to the paddock so they are more vigorous (e.g. more disease tolerant varieties) and competitive with weeds,
- ensuring insect management and plant nutrition is optimal so as to maximise early growth and competition,
- selective herbicides, especially in combinations or sequences which allow for maximum control of resistant weeds, and
- hand rogueing of plants, especially wild radish.

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CHAPTER THIRTEEN

MARKETS AND MARKETING

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INDUSTRY PROFILE

Ian Wilkinson and Jamie Henderson

Wheat is the largest of Western Australia's agricultural industries with an average Gross Value of Agricultural Production (GVAP) over the five years to 1998/99 of $1.6 billion. In 1998/99 the wheat GVAP was $1.7 billion. Over the same five years wheat represented 37% of the total GVAP and 44% of the State's value of agricultural exports.

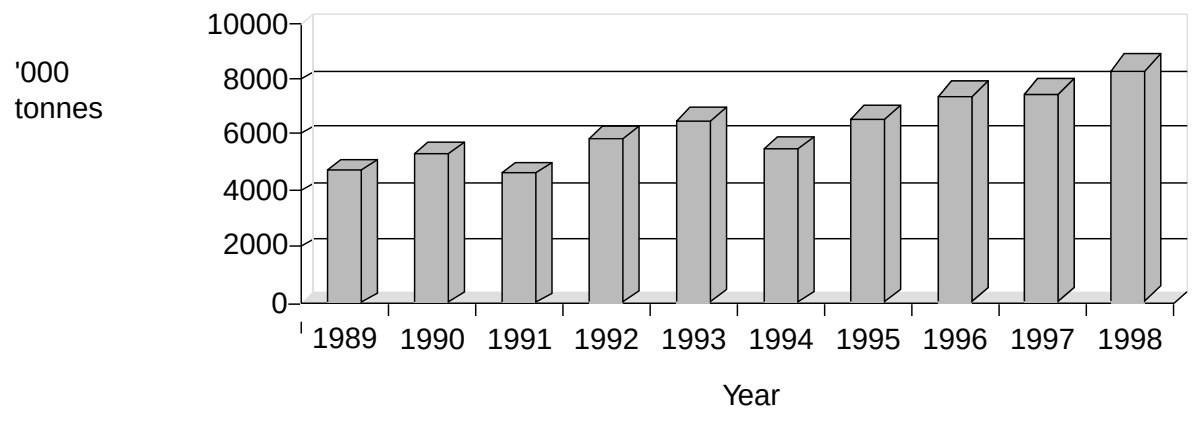
Western Australia is the major producer of wheat in Australia. In 1997 the State produced 7.6 million tonnes of wheat (40% of Australia's wheat production). Production over the 10-year period to 1999 is shown in Figure 13.1.

The Western Australian wheat industry is export focused with around 95% of production shipped to overseas markets. Currently approximately 300,000 tonnes of wheat is processed locally. The level of processing is increasing and manufacturers are looking to export their products, particularly to the Asian region.

The Western Australian cereal industry is advanced and innovative compared with both the eastern States and international competitors. The 1998 Australian Grain Industry Report prepared by ABARE showed that Western Australian grain farms had nearly double the farm business profit when compared to the Australian average. The sector contributes significantly to the State, both financially and socially, with the infrastructure of many country towns revolving around the wheat industry.

There are around 6000 committed wheat growers in Western Australia. The average age of the farm operator in Western Australia is 52 years, with 18% being under 40 years old. Growers are serviced by over 300 agribusiness consultants and agronomists who extend the latest technology to growers. In 1998, ABARE reported that WA grain farmers spend $2,763 on consultants (average per farm), with 45% of grain farmers utilising a consultant. This compares with the Australian average of $1,826 and 28%.

Figure 13.1



Wheat production in Western Australia

MARKETING OF AUSTRALIAN WHEAT

Options for the marketing of wheat have become more diverse as regulation in the industry is removed. The pricing mechanisms available for selling wheat have become increasingly more complex as the AWB Limited (AWB) give farmers more pricing options. Farmers will need to develop a more detailed understanding of marketing and pricing mechanisms to ensure that they achieve the best farm-gate return available for their product. On top of this farmers are becoming increasingly aware of the opportunities for better price-risk management than they have had in the past.

AWB Ltd

The AWB is a national and international grain-marketing organisation that markets wheat and other grains on behalf of Australian grain growers and provides finance to growers, to make payments in advance of revenue received on wheat sales. The AWB is Australia's fifth largest exporter, with annual sales revenue in excess of $4 billion. It serves Australia's 40,000 grain-growers in marketing wheat to more than 50 countries and 100 individual customers.

On 1 July 1999 Commonwealth legislation was enacted to move the AWB from its role as a statutory authority to a grower-owned and controlled organisation. The AWB is now a stand alone corporation under Australian Corporations Law, run by its own elected board, owned and controlled by Australian wheat growers, and with an opening capital base of around $550 million.

The only remaining area of substantive Government involvement in the AWB's current operations is in the so-called "single desk" export powers for wheat. Legislation has been retained to give the AWB the sole right to export wheat in bulk. This is contingent on the review of the legislative arrangements that will be carried out under the auspices of the National Competition Policy.

AWB Limited will have two subsidiary companies – AWB (Australia) Limited and AWB (International) Limited:

- AWB (Australia) Limited will be responsible for domestic wheat and other grain trading and the export of non-statutory grains, as well as other commercial ventures undertaken.
- AWB (International) Limited will be the subsidiary company responsible for the wheat export pools and will be focused on maximising pool returns.

As a grower-owned private company, the focus of the new AWB will be to maintain a commercial focus on the creation and maximisation of returns for its shareholders. The parent company AWB Limited will be responsible for all funding and the provision of shared businesses and corporate services. This company will act as borrower for the AWB Group and will on-lend to the subsidiaries, particularly the pools subsidiary to fund advance payments to growers.

Being the sole exporter of Australia's wheat, the AWB carries the collective risk of international price and financial exposures on behalf of Australia's wheat growers.

The AWB has a number of marketing mechanisms for farmers to utilise. The most popular, and the mechanism for the majority of wheat receivals, is the pool. The AWB has established a series of pools based on variety, quality and protein windows, some of which also contain segregations and payment scales based on the protein level of the wheat. The wheat received is stored according to these grades and segregations. This allows the AWB to offer more direct feedback on prices for different quality wheats. It also enables the AWB to meet the needs of the customer more specifically, as they have a full range of wheat qualities available to market.

The grades of wheat produced in Western Australia are:

- Australian Standard White (ASW) – a versatile medium to low protein wheat suited to straight milling or blending. Used to manufacture of steamed buns, instant noodles and some types of flat bread.
- Australian Premium White (APW) – a blend of harder grained varieties with a minimum protein of 10%. Targeted at instant, fresh and Hokkien noodles, Middle Eastern and Indian style flat breads and Chinese steamed bread.
- Australian Hard 1 (AH1) – contains specific hard grained varieties of superior milling quality. It has a minimum protein of 11.5% and excellent milling extraction rates. It is aimed at European pan style breads, Middle Eastern style flat bread, some Chinese steamed products and Chinese style alkaline noodles.
- Australian Hard 13 (AH13) – only nominated Australian Hard varieties can be delivered to this segregation, at a minimum of 13% protein.
- Australian Noodle (ASWN) – contains very specific soft-grained wheat varieties. Formed to supply the white salted noodle market in Japan and South Korea, which requires unique starch quality.
- Australian Soft (AS) – a unique blend of white soft-grained club wheat varieties with a maximum protein level of 9.5%. Suited for end-users making sweet pastry, biscuits, cookies, pastries, cakes, steamed buns and snack foods.
- Australian Durum (AD) – selected durum varieties with vitreous, amber coloured kernels and a minimum protein content of 13%(AD1), 11.5% (AD2) or 10% (AD3). Milled to produce semolina, which is ideally suited to the production of high quality wet and dry pasta products.

Pooling allows the AWB to sell the season's wheat harvest over a period of time, smooth out price variations in the world markets, and return an average price to growers. At harvest, farmers receive an advance payment

■ MARKETING OF AUSTRALIAN WHEAT *(continued)*

of 80% of the expected pool return. This gives farmers some payment for their product even though the product hasn't been sold. The AWB spreads the sales of the pool over time and in different markets and environments to try and maximise pool returns. The pool is usually finalised in 2-3 years and the farmers receive a final payment on the pool. This covers the remaining 20% of the return. This system requires the AWB to borrow large amounts of money to cover the harvest payment and the government previously underwrote this borrowing. The AWB will now finance the advance payments using the capital accumulated through the Wheat Industry Fund levy, which has been converted into shares allocated to the growers who have made the contributions.

The AWB Ltd in 1999 has launched 4 new pricing mechanisms for pools. The first is the 80% up-front harvest payment, which will operate, as has been the case in the past but will incur a $2/t underwriting fee and a financing fee.

The second option is the quarterly payment, which is an Australian dollar payment in four quarters as the AWB Ltd progressively sells the pool. The option will incur minimal borrowing costs but the farmer will not know exactly what he/she will receive for their wheat in the pool.

The third option is the quarterly payment in US dollars. This is the same as the second alternative but payments will be received in US dollars and the AWB Ltd will not undertake any foreign exchange management of those funds. This puts the onus on the farmer to undertake a foreign exchange management strategy.

The fourth option is the quarterly payment in US$ per tonne converted to AU$ at the spot rate at the time of payment.

The AWB has several other mechanisms for selling wheat, which include the cash payment for delivery to the port. This offers an immediate and known return for farmers, however the price for port delivered wheat is often lower than the final pool return, even after discounting future pool payments.

Farmers have the ability to hedge their wheat sales, by buying (or selling) Chicago Board of Trade (CBOT) and/or Sydney Futures Exchange (SFE) futures and options in order to hedge the price they receive for their wheat. The international futures prices can be used as a price setting mechanism for wheat, at planting or at any time through to when the wheat is physically sold. The Chicago Board of Trade is the major grain trading futures exchange in the world and the price of the wheat futures on the CBOT significantly influence the final pool price of the AWB.

It is likely that an increasing number of marketing mechanisms will come on-line for use by farmers. Information on these mechanisms can be obtained through AWB Ltd, agribusiness consultants and marketing newsletters.

Domestic Marketing Arrangements

The domestic (Australian) wheat market was deregulated in 1989. Since then, producers have had greater options available in selling wheat and have had greater control over their financial outcome for the year.

The domestic market is relatively small when compared to the export volumes from Australia each year. For Western Australia around 200,000 – 250,000 tonnes would be utilised for milling to produce flour, most of which is consumed domestically. In parts of the eastern States, however, the domestic market has become a significant user of wheat, particularly in years where there are production problems for wheat.

The domestic market is limited by the small population of Australia compared to our production of wheat, but has been expanding in recent years as the consumption of noodles and pasta has increased. The instant noodle market has grown strongly as consumers increasingly seek convenience foods. This has seen the establishment of a number of noodle manufacturers in Australia.

As the domestic market for wheat is not regulated, there are a number of options for marketing wheat:

1. Direct purchase by processors from farmers – usually for a cash price, with the potential for on-farm storage and deferred delivery. There is a small but increasing amount of high quality wheat being purchased by forward contracts between growers and millers. Such contracts would specify such things as variety, protein, moisture, screenings, etc. By targeting good farmers in specific areas, it is possible to get reliable supplies of wheat of very specific quality. Farmers benefit from having very direct feedback as to the quality requirements of the processor.
2. Purchase by domestic traders/merchants – who will source packages of wheat of the required specifications for the processor. Again forward contracts can be utilised and specific qualities can be specified. An advantage of processors using traders is in utilising existing expertise and local knowledge that is available to source wheat of the required quality. Also, the logistics of storing, handling and transporting the grain can be organised on behalf of the processor.
3. Sell direct to the AWB Ltd – to its trading division, which can provide similar service to other traders, including cash prices and premiums for specific quality traits.

Prices are quoted at a number of levels; such as free on board (FOB), delivered port, or delivered to processor. Because of this it is important for growers to convert all prices to a farm-gate return when comparing wheat prices on offer. The basis of pricing terminology is explained in the following diagram:

MARKETING OF AUSTRALIAN WHEAT *(continued)*

WHEAT PRICING TERMINOLOGY

CIF – COST INSURANCE FREIGHT
Landed price at export destination (includes shipping and insurance costs)

↓ minus shipping and insurance costs

FOB – FREE ON BOARD
Price of wheat loaded onto vessel ready to sail

↓ minus AWB finance (borrowing to support pool payments) and administration costs (includes promotion, currency and commodity risk cover)

POOL RETURN
Average FOB return less AWB finance and administration costs

↓ minus storage and handling charges
+/- port allowance

DPB – DELIVERED PORT BASIS
Value of wheat delivered to port,
ie, NPR – CBH charges (plus or minus port allowance for wheat)

↓ minus freight to port

SILO RETURN
Value of wheat on delivery to silo
ie, DPB – Freight to Port

↓ minus
cartage to bin, CBH tolls
levies
skeleton weed ($0.15)
Industry levy* (1.03% 'farm gate return')
1% GRDC
0.03% residue testing

FARM GATE RETURN

*The Wheat Industry levies are calculated on an estimated farm gate price.

■ MARKETS FOR AUSTRALIAN WHEAT *(continued)*

Major Markets

Australia produced an average of 13.7 million tonnes of wheat per annum over the last 5 years, making Australia the 8th largest producer of wheat in the world. While this does not make Australia a major player in terms of production, we export a large proportion of our production due to our small population base and consequently our low domestic demand. Supply and disposal of Australian wheat is shown in figure 13.2.

While prices received on the export market are largely dependent on world prices, the sale of grain domestically offers producers a greater range of market opportunities and pricing mechanisms.

The Domestic Market

The domestic market is relatively small but still significant to the Australian industry and economy. Deregulation of the domestic market in 1989 has allowed Australian grain growers to have some freedom in where and how they sell their grain.

The domestic wheat market is dominated by several grain trading companies and many smaller traders and processors who purchase wheat to meet their processing needs. These usually have a specific quality specification depending on the end use.

Use of wheat on the domestic market is in three categories; human/industrial, feed, and seed use. Over the past five years, human/industrial and seed use of Australian grains has been increasing slightly. The use of wheat for feed purposes has been increasing at a more rapid rate and showing signs of continued expansion in the future.

A comparison of the production of flour for various end-uses in Australia is shown in the table 13.1.

Table 13.1 Comparison of the production of flour for end-uses

	Tonnes produced	
End Use	**1988**	**1998**
Starch/Gluten	300,302	459,803
Other Industrial	5,876	3,816
Bread bakers	562,705	777,243
Pastry cooks	93,317	65,418
Biscuit	81,379	84,315
Pasta	44,210	76,315
Packet and Mixes	79,709	115,798
Food Manufacture	97,349	127,798
DOMESTIC TOTAL	1,264,847	1,710,506
Export	85,881	202,051
TOTAL FLOUR	1,350,728	1,912,557

The domestic grain industry is able to increase value through further processing of whole grain. Opportunities for growers in terms of marketing domestic grains provides some potential benefits to the grains industry and alternatives to exporting, which is vulnerable to price fluctuations due to an unstable world market. Total Australian wheat use for milling is around 2 million tonnes per annum and milling volume is only expected to increase slowly in line with population increases and increased export opportunities for flour.

The more prominent areas of further processing are the beef feedlot industry, the pig industry and the poultry industry. In recent years these have been expanding their use of feed grain and are becoming more quality specific as their operations increase in efficiency and intensiveness. This has seen the introduction of specialist high-yielding feed wheats in high rainfall parts of Australia.

Apart from the stockfeeders there are a large number of other potential domestic niche markets for wheat. Some of these niches have already become significant to the wheat industry, and include:

- Starch and industrial wheats;
- Durum wheat for pasta;
- Novelty wheats (purple wheats);
- Wheats for ethanol production; and
- Fodder wheats for hay, chaff and grazing.

Export Market

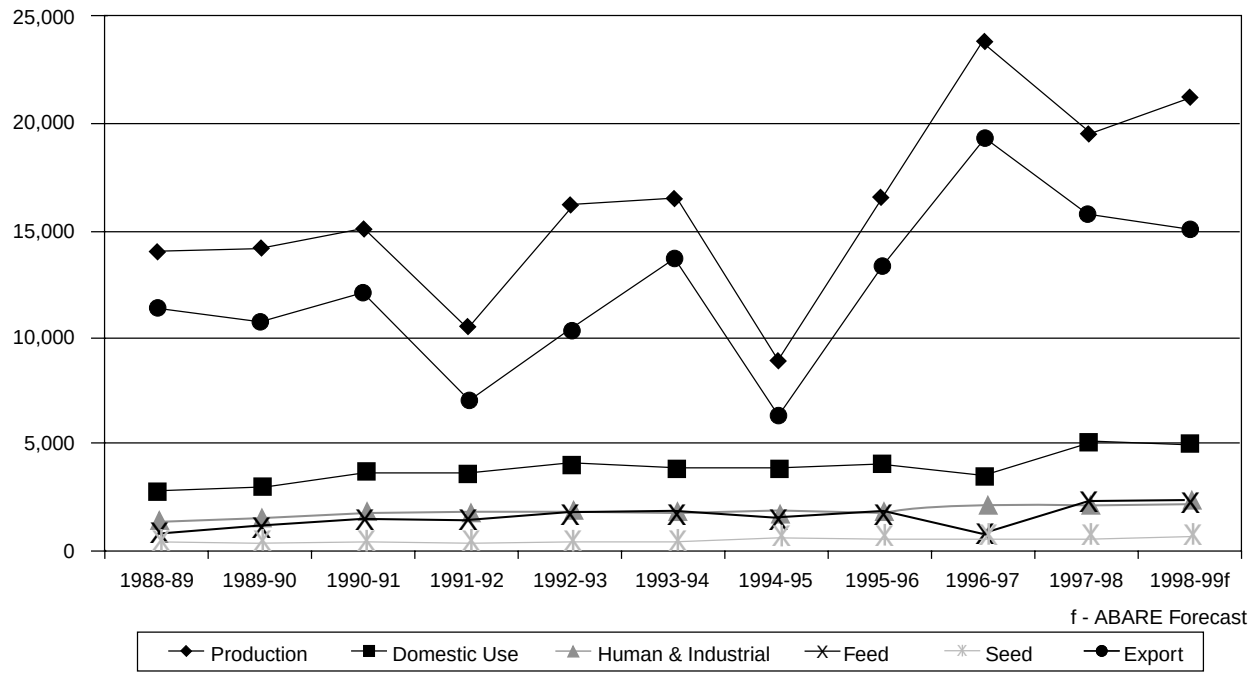
The major competitors for Australian wheat exports are the USA, Canada, the European Union and Argentina. Two products dominate world cereal trade – wheat and corn – which account for around 85% of all cereals traded. World wheat trade (around 100 million tonnes) is dominated by the US, which supplies a third of all exports. Other major players are Canada at 20%, the EU at 19%, Australia at 10% and Argentina at 7%.

World wheat markets can be broadly categorised into three main types – commodity (price driven, low loyalty), relationship (price enhancement, some quality requirements, technical assistance provided) and branded (quality driven, high loyalty, price premiums). This is a dynamic situation. Over time, competition will develop a product and service similar to a branded market.

There is a trend towards reduced regulation of purchasing arrangements in the major wheat importing countries (eg. COFCO in China, BULOG in Indonesia). This will open up opportunities for the Western Australian industry to deal more directly with the users of cereals enabling the development of relationship markets, and perhaps in the longer term more branded markets. The majority of wheat sold around the world is sold as a commodity, but AWB Ltd is looking to increase the proportion sold into higher paying markets. Over time these premiums will be passed back to growers as a strong signal of market preferences, thus allowing growers to tailor production to market requirements.

MARKETS FOR AUSTRALIAN WHEAT *(continued)*

Figure 13.2



Supply and disposal of Australian wheat

As can be seen in figure 13.2, the vast majority of Australian wheat production is exported each year. The production in Australia varies depending on the weather conditions, but due to Australia's diverse climates for growing wheat the production level is more consistent than in most other wheat producing countries. The export level of wheat depends on this variation in production with increases in good production years and decreases following poor seasons. The domestic market is relatively stable in its use of wheat, as it is more dependent on the demand of the processors, which does not usually change a great deal from year to year.

The AWB Ltd has established a large number of international customers that consistently buy Australian wheat.

The major international markets for Australian wheat are: Indonesia, Japan, Taiwan, Saudi Arabia, Egypt, India, Malaysia, United Arab Emirates, China, South Korea, Iran, Iraq and Yemen. The sales to these markets are very variable with the changing political, climatic and market situations in each country. A good season may reduce imports from Australia to almost nothing where-as a bad season increases imports dramatically. Australia has developed markets that see Australian wheat as high quality and are in many cases willing to pay a small premium for the wheat. Sales to these countries are negotiated and enhanced by the AWB international units, which are located in South East Asia, Hong Kong (North Asia), Tokyo, and Middle East/Africa.

In recent years the AWB has been very conscious of the needs of the customer and has placed a lot of emphasis on customer service. It also researches market trends to match the wheat varieties grown and pool specifications with requirements of the customers and processors. The aim of this marketing strategy is to develop customer loyalty, which will produce more consistent sales with customers that value Australia's product over our competitors.

Major End-Uses for Australian Wheat and Quality Requirements

Australian wheat has achieved a reputation for producing clean, white wheat with low screenings, insect free, sound and with low moisture content. The primary quality differentiating Australian wheat in the international market place is that it is white grained (most wheat traded is red wheat). Australia has a climate that is suited to the production of white wheats, which have high extractability in flour production and are therefore more cost effective for flour millers.

These qualities and the increasing efforts of wheat farmers to tailor their varieties and protein content to meet end-user requirements, allow the Australian wheat industry to supply more specialised markets rather than solely providing a bulk undifferentiated product.

Australian wheat is used to produce a large number of

■ MARKETS FOR AUSTRALIAN WHEAT *(continued)*

different products for a wide range of cultures throughout the world. These include traditional breads (flat breads, steamed breads and many others), noodles, biscuits, cakes, and pasta.

There is a great diversity of products that can be made from varieties of wheat grown in Australia. Various institutions within Australia including state Departments of Agriculture, CSIRO, the Bread Research Institute, and the Academy of Grain Technology, have been researching how to best meet the needs of the customers and Australia is now at the forefront of research into the quality requirements of different end-uses of wheat.

Bread

There is a range of different bread types that are made throughout the different cultures. These breads have different ingredients, preparation, processing and cooking methods and even in many cases used different grades and types of flours. These breads include Loaf or Pan Bread, Flat Bread and Steamed Bread.

Loaf or Pan Bread

Loaf or pan bread is the standard bread that is eaten in most of the western world. Produced in a wide range of shapes it is commonly white bread that is produced daily and consumed over 1 or 2 days. Recent years have seen some diversification of pan breads produced with multi-grains, high fibre, and wholemeal, becoming more significant in the market place.

Flat Bread

Exports of wheat destined for flat bread production in the Middle East form a significant proportion of Australia's wheat exports. Increased popularity of this product within Australia has lead to a growing domestic demand.

Flat breads may be single or double layer breads and include Baladi Bread, Naan, Tanoori, Lavash, Sangak and Arabic bread. Flat breads are consumed as a staple food in many countries and are traditionally made by hand at home or in small, localised bakeries. There has been a big shift in the last ten years towards centralised production in more fully automated bakeries.

Baladi bread is the major bread type consumed in Egypt. It is a two-layered flat bread that is made from high extraction flour, yeast, salt and water and is mainly made by hand. Tanoori (taftoon) bread is a single layered flat bread consumed in the gulf countries of Iran, Iraq and Syria.

It is one of the Arabic breads also known as pocket, pita, or lebanese bread which is created by separating the two layers during baking.

The Australian industry and the consumption of flat breads have expanded considerably in recent years with flour consumption for flat bread production increasing from 2,300 tonnes in 1986 to 5,600 tonnes in 1989. The product was initially manufactured in small ethnic bakeries and sold within the local community, but with acceptance of the product, the size of these bakeries has increased. Flat breads have now become widely available in the major supermarket chains.

Steamed Bread

Consumption of Chinese steamed bread is predicted to increase in both China and other Asian countries. A contributing factor to this growth is that, as a traditional product, steamed bread is also a convenience food. With steamed breads now marketed through supermarkets and fast food outlets, the technology requirements for production and shelf-life expectations are becoming more demanding.

There are three types of steamed breads produced. These are:

- Northern Style, made out of hard wheats that have strong dough and are high in protein.
- Southern style, made out of hard wheats but with lower dough strength and protein levels, and
- Cantonese style buns, made from the softer grained wheats. These are usually sweet and eaten as a snack food.

Noodles

There are a number of different noodle types, which fall into the two categories; yellow alkaline or white, salted noodles. The main yellow alkaline noodle types are Cantonese, Hokkien, Ramen and instant noodles. The main white types are Udon and Long Life noodles. Some white instant noodles are also produced. Yellow alkaline noodles are made with various wheat qualities ranging from ASW to AH and APH. The ASW-N segregation is ideally suited to the production of white, salted noodles.

About one third of Australia's wheat production is used in the manufacture of Asian noodles. This represents about $800 million worth of wheat. About 70% of this wheat is from Western Australia. Japan is one of our most important noodle wheat markets and it imports about 18% of its wheat from Australia.

In Asia 65-70% of wheat is consumed as noodles. Noodle consumption world wide is increasing with Asian consumption expected to increase to 85 million tonnes and imports of noodles into Asia are expected to increase to 17 million tonnes by the year 2000.

The Asian market is very quality conscious in terms of noodles and the consumers are seeking good brightness, colour and stability of colour as well as good firmness, chewiness and smoothness. Considerable work is being carried out in Australia to determine which quality characteristics are appropriate to produce each noodle type.

Biscuits, Cakes and Pastries

Sweet biscuits, cakes and pastries are best made from flour produced by milling low protein, soft grained wheat. Again, there is strong growth in consumption in the Asian region for these products, but from a relatively low base. Currently there are export markets for 350-400,000 tonnes, and further expansion will be reliant on enlarging our share of this market.

MARKETS FOR AUSTRALIAN WHEAT *(continued)*

Pasta

Pasta consumption is another area that has seen great expansion in the 1990's. Australian consumers have begun to diversify their tastes and this has lead to increased pasta and noodle consumption. Strong growth in pasta consumption is also occurring in the Asian region, but again this is from a low base.

Pasta is traditionally made out of 100% Durum wheat, which is milled to make semolina that is then used to produce the pasta. More detail about Durum wheat and the industry in Australia and the establishment of an industry in Western Australia can be found in the Chapter on Durum wheat.

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CHAPTER FOURTEEN

SPECIAL WHEATS

Authors: A Impiglia, B. Mullan, R. McTaggart

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■ DURUM

Alfredo Impiglia

ORIGIN

Wheat was probably domesticated around 12,000 – 15,000 B. C. in the Near East area known as the "Fertile Crescent", a mountainous hilly region in the upper reaches of the Tigris-Euphrates drainage basin. Great variability through thousands and thousands of generations has been increased in tetraploid (e.i. durum wheat) and hexaploid (e.i. bread wheat) by their ploidy level and by the survival possibility of mutations, which permit progress in human utilization of these cereals.

Most certainly, wild tetraploid wheats were already widely distributed in the Near East when humans started harvesting them in nature. Their general size, and particularly the size of the spike and the kernels, made them much more worthwhile for domestication than diploid wheats. Moreover, the spikelet was structured to differentiate two or three flowers, and then each spike, consisting of 15-20 spikelets, could provide 30-50 kernels. Therefore, the potential of tetraploid wheats was quite interesting from the beginning. The two wild tetraploid types, *T. araraticum* and *T. dicoccoides*, were both domesticated. The first gave *T. timopheevi* and the latter gave *T. dicoccum*. *T. dicoccum* spread from the Near East to large areas of the Mediterranean and Middle East, to Egypt, and to Ethiopia. Later, the more advanced types, characterized by naked kernels and much wider adaptation, belonging to *T. turgidum* var. *turgidum* and *T. turgidum* var. *durum* (durum wheat) spread to all Europe, the Middle East and North Africa. During the Roman Empire, most of the wheat carried to Rome from the colonies belonged to the *T. durum-turgidum-dicoccum* group. The basic differences between the *T. turgidum* and *T. durum* types are in the kernel structure (starchy in *T. turgidum* and vitreous in *T. durum*) and in the better adaptation of *T. durum* to semi-arid conditions and of *T. turgidum* to more continental and humid climates. Both types were used for bread making and for a number of other uses such as lasagna sheets, some of which are still common today. Among all cultivated tetraploid wheats, *T. durum* is by far the most important, even though it is grown in less than 10% of all the area cultivated to wheat, the remainder being represented by the bread wheat, *T. aestivum*.

GENETICS

All wheats, durum included, belong to the genus Triticum, a member of the grass family, Gramineae (Poaceae). Durum is a typical annual cereal. It is a tetraploid wheat with genomes AABB [2n=4x=28]. Early cytogenetic studies led to the conclusion that durum wheat (genome AB) is derived from a tetraploid hybrid of diploid T. boeoticum or T. baeoticum (donor of the genome A) x an unknown wild grass (donor of the genome B). Each of which contributed a set of seven chromosomes (genome) (Sax, 1922; Kihara, 1924). However, Konarev et al. (1979), from studies conducted on seed storage proteins, found that the genome A in the T. turgidum lineage was contributed by T. urartu. In 1988, Dvorak et al. concluded that tetraploid wheats are closer to the genome A of T. urartu than to the genome A of T. boeoticum. As for B genome in durum, it seems to have originated from T. speltoides (Dvorak and Zhang, 1990, Dvorak et al., 1993), but the B genome origin is still not so clear. The durum kernel has the hardest texture of all wheats and it is also larger and more vitreous than bread wheat. The durum endosperm contains a higher concentration of xanthophyll or lutein pigments than bread wheat and the desirable milling product is generally semolina, which is a coarser flour used for making pasta.

■ DISTRIBUTION, PRODUCTION AND CONSUMPTION

Durum covers approximately 21 million hectares worldwide, spread over many countries. More than 80% of the total land under durum cultivation is in the Mediterranean basin (Srivastava et al., 1988), where rainfall and temperature show large and unpredictable fluctuations from year to year. Another major source of durum is North America and prediction in Australia is increasing rapidly.

Due to its greater adaptability in harsh environments than bread wheat, durum has been concentrated in the driest areas of the West Asia and North Africa (WANA) region and South Europe.

Production of durum in the world is relatively stable at about 30 million tonnes. In countries with a long history of durum improvement such as Italy, France, Canada and the United States, production is stable but quality is improving. In countries with a long history of durum production, but where there has been a recent impetus for durum improvement, such as Mexico, Turkey, Tunisia, Spain and Syria, yields and production are increasing (table 14.1).

In Australia, durum production started in northern New South Wales and southern Queensland and spread more recently to South Australia. Commercial production began in Western Australia in 1998 and production of over 100,000 tonnes is estimated in five years time. Production in 1998/99 and estimated production in 1999/2000 are shown in table 14.2.

Production in Australia has been increasing with a record crop in 1998 of over 400,000 tonnes. However, production has fluctuated in the last 10 years between 50,000 and 400,000 tonnes taking Australia from an importing to an exporting situation, depending on season.

The major exporters of durum grain (including semolina) in the world are Canada, the USA and the European Union (EU). Exports from the USA and the EU have declined over the past 10 years but have increased slightly from Canada. New exporting countries such as Turkey, Syria and Mexico have partially compensated for the decline in exports from the more traditional countries above.

Table 14.1 – World production, area and yield of durum wheat (mean 1985 to 1995). [Source: International Grain Council]

Region	Production ('000 t)	Area ('000 ha)	Yield (t/ha)
Europe	7829	3003	2.6
EU	7778	2981	2.6
North & Central America	6712	3347	2.0
South Americ	164	87	1.9
Asia	8119	5438	1.5
Middle East	6384	4323	1.5
Africa	3446	3140	1.1
World	28611	17260	1.7

The major importers are the EU (Belgium, Italy), the Americas (USA, Venezuela), Asia (Turkey, Bangladesh, Japan), the Far East (unspecified countries) and Africa (Algeria, Libya, Morocco, Tunisia); Figure 14.1 shows the world durum trade where some countries are both exporters and importers of grain and semolina.

In the past 10 years the price of durum wheat in North America has risen from about $US120/tonne to about $US270/tonne (FOB). Price rises since 1990/91 has been associated with constant increases in demand rather than with decreases in availability.

In Australia there has been a premium for durum higher than bread wheat at the same protein percentage that varies from A$40 to about A$115/t depending on the grade and the international market price (Figure 14.2). For the last 6 years the average differential in price was A$64/t between durum grade 1 at 13% protein (ADR1) and Australian Hard at 13% protein (AH13) in WA. In 1994/95 durum pool was not available.

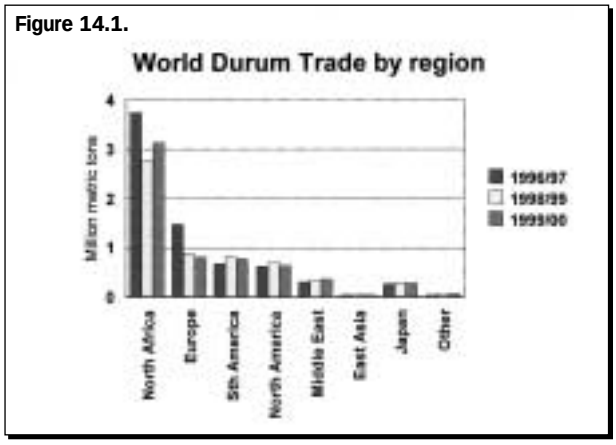
Table 14.2 – Durum production in Australia (1998/99 and 1999/2000 forecast)

State	1998/99			1999/2000*		
	Hectares ('000)	Grain Yield (t/ha)	Production ('000 t)	Hectares ('000)	Grain Yield (t/ha)	Production ('000 t)
NSW	133	2.3	300	150	2.7	500
SA	33	2.6	85	35	2.6	90
QLD	NA	NA	15	NA	NA	20
WA	2	1.5	3	19	1.6	30
Australia			403			650

* Estimated

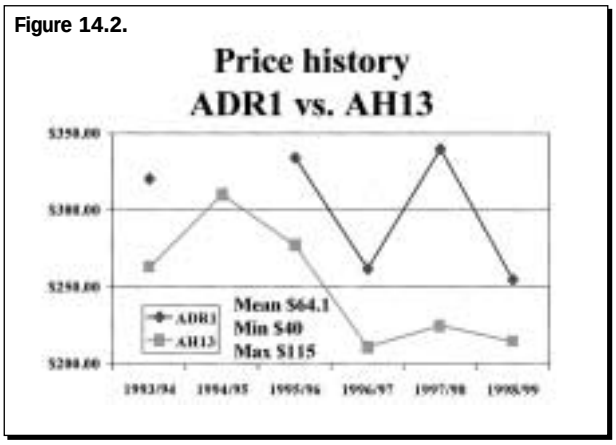
■ DISTRIBUTION, PRODUCTION AND CONSUMPTION *(continued)*

Figure 14.1.



World durum trade by region.

Figure 14.2.



Price history comparison between ADR1and AH13.

Durum wheat production and productivity is not stable due in part to the climatic conditions under which the crop is grown and in part to biotic stresses.

Durum is mainly used for human consumption and the major end-product is pasta.

Global consumption of durum has been divided into groups according to broad regions in table 14.3. The dominant use is for pasta except in the WANA region where bread and other traditional end-products are important.

Table 14.3 – Major uses of durum in the world.

Consumer use	WANA (%)	Europe (%)	Americas (%)	Australia (%)
Pastas	20	94	97	98
Bread	40	3	1	1
Couscous & Burghul	30	2	1	1
Others	10	1	1	0

Estimated by Varughese (1975) re-evaluated by Nachit (1994) and Impiglia (1998)

■ GRAIN QUALITY AND END-PRODUCTS

The quality of durum grain is strongly reflected in the quality of the end product. The suitability of durum for pasta manufacture is a function of a combination of its proteins, carbo-hydrates and lipids. High protein percentage alone does not guarantee optimum pasta quality since the quality of the proteins (e.i. seed storage proteins) are a key factor for good cooking properties in the pasta. Quality characteristics of durum that make it suitable for pasta are also its vitreousness, starch structure and yellow pigments. Desirable characteristics in a sample of durum are high protein percentage and test weight, low ash content and large plump grains.

Elasticity and extensibility of the gluten complex in the grain, confer the viscoelastic properties to the dough, which make durum well suited for pasta as well as couscous, burghul, frike, bread and other Mediterranean local food product. Functional properties of durum flour products are mainly determined by the seed storage proteins present in the endosperm (Kasarda *et al*., 1976). Extensive studies have been conducted on the variation and genetic control of the seed storage proteins, gliadin and glutenin, of durum and bread wheat and their association with wheat end-use quality (MacRitchie et al., 1990).

For a good end-product in durum, it is important to have large protein content with a good amino acid composition. Other substances like vitamins, minerals, and starch are relatively less important because they are generally present in other parts of the human diet.

Durum kernels are normally hard and similar in protein level to the hexaploid hard wheat. However, in Western Australia the Australian durum varieties have shown higher protein levels than the current bread wheat varieties at the same pedo-climatic conditions. Virtually all varieties have amber, vitreous, and rather large kernels. However, durum proteins are deficient in some essential amino acids such as lysine and threonine, which is the limiting nutritional factor; this is common for most cereals. For this reason the first priority for a breeder is to improve the total amount of proteins.

The protein content is usually about 13% in durum wheat (ADR1 grade), but may reach 22%. Protein content is strongly affected by moisture, temperature, and nitrogen supply. Kernel disorders due to stresses and diseases may also affect the durum grain quality. Yellow berry or starchy kernels is caused by lower protein content in the grain which is reflected in low semolina yield when the kernels are milled (Matsuo et al., 1980). Yellow berry is also caused by nitrogen deficiency, and related, indirectly, to water supply. Shrunken grain is also an undesirable character in durum wheat.

However, the quality of the proteins present in the endosperm also plays an important role for a good end-product. The seed storage proteins, gliadin and glutenin (also called gluten proteins) are responsible for the rheological (viscosity and elasticity) properties of the gluten and affect the biological value.

There are several grain quality factors related to a good durum cultivar and its end-product (table 14.4). Quality tests are applied to grain, as well as semolina, spaghetti or bread or other end-products. Therefore, the criteria for durum wheat grain quality are botanical, physical, and chemical (table 14.5).

Table 14.4 – Grain quality factors for durum end-use products.

Product	Quality factors
Bread	High gluten strength, medium-high protein content, light color
Pasta	high gluten strength, high protein content, high yellow pigment content, vitreousness, high semolina yield
Couscous	As for pasta
Burghul	As for pasta plus large kernel size
Frike	Immature large kernels at dough stage, hardness
Export	As for burghul

Williams *et al.* (1989)

Table 14.5 – Criteria for grain quality in durum.

Botanical	Species, cultivars
Physical	Test weight, thousand kernel weight, kernel size, vitreousness, moisture, flour colour, shrunken broken, milling quality,
Chemical	Moisture content, protein content, protein quality, yellow pigment alpha-amylase activity, fat acidity, ash

Impiglia *(not published)*

Durum is processed into semolina, which is coarser than standard wheat flour. Semolina extraction is around 68-70%. Pasta, couscous, burghul and frike products should be made only from durum semolina, due to the particular properties of the grain. All those products require the same grain characteristics as for pasta, while durum bread, which has a longer shelf life than bread made out of bread wheat, has different quality requirements.

Durum is not only a food crop, but it also has a broad use in animal feeding and in the industrial sector. Durum grain is a good livestock and poultry feed when used as a part of the ration. Most wheat milling by-products, especially bran, are utilized in the preparation of commercial livestock feeds. In some areas, durum is grazed each year while the plants are in the juvenile stages. The same fields are later harvested for grain. Controlled grazing allows efficient utilization of durum as forage. In some cases the green crop is utilized as hay or silage. Durum

■ GRAIN QUALITY AND END-PRODUCTS *(continued)*

straw is often used as part of the roughage fed to ruminants, and is used extensively for livestock bedding, for instance in Syrian dry-lands. Industry utilizes some durum straw in making paper, wallboard, packing material, various adhesives for paper boxes and plywood, paper, alcohol, and other products. A minor use of the starch is in the textile industry.

Breeding efforts, conducted particularly during the last two decades by national and international centres, have contributed to a substantial and continuing trend of improvement of durum yield and grain quality.

MORPHOLOGY

Durum has a rather strong root system, with a number of fibrous and long roots growing to a depth of more than 1 m in good conditions. The stem is cylindrical, erect, and sometimes solid (Australian durum varieties have solid stems), but more often hollow, subdivided into internodes by well-identified nodes, each one being the origin of a leaf. Leaves are distichous, composed by a basal portion, the leaf sheath, and a terminal portion, the leaf. At the attachment of the leaf, on the leaf sheat, there is a thin trasparent membrane, the ligule, with two small lateral appendices, called auricles. Flowers are typically hermaphroditic, clustered in sessile or nearly sessile spikelets that are layered upon each other to form a spike. Flowers vary from two to six per spikelet in durum (but up to eight in bread wheat). In durum, the superior glume has an awn 3-20 cm long. At the base of each flower are two small bodies, lodicules, which become turgid at the blooming stage, inducing the opening of the glumes and then of the flower. The fruit is a large caryopsis, generally with a large flint endosperm and a flattened embryo located at the apex of the seed and close to the base of the flower.

DEVELOPMENT

The life cycle of durum can be subdivided into three main phases: 1) the embryonal phase, which is from the flower fertilization to the ripening of the seed caryopsis; 2) the vegetative phase from seed germination to the first differentiation of the apex; and 3) the reproductive phase from the first differentiation of the inflorescence, the spike, to blooming. Transition from one phase to the next is controlled both by environmental and genetic factors and their interaction.

The physiological processes connected with seed germination can take place at 1-2ºC, but the optimal temperature is 20-25ºC. During this first phase, water uptake occurs and the kernel reaches about 150% of the initial weight in 10-15hr. Imbibition triggers cell elongation and biochemical activity. The embryonal shoot and roots start growing, emerging from the pericarp. Mitosis starts 12-24hr after the beginning of the germination process, depending upon the temperature. After germination, at the emerging of the fourth leaf, adventitious buds appear at the insertion of leaves, starting the tillering process. These lateral shoots are already present in the embryo but are developed only if the minimum temperature is less than 13-15˚C for at least 20-30 days after germination. Adventitious roots are formed at the base of each tiller; which are largely physiologically independent of each other up to the end of the development cycle. These clusters of roots grow rapidly into the soil functioning both to take up water and minerals and to anchor the plant. In normal cultivation conditions, each plant consists of one to three tillers, each one developing into one head. In optimal growing and cultivation conditions a larger number of tillers and heads per square meter can be produced.

The vegetative phase ends with the differentiation of the apex into the spike primordia. These primordia then develop at the same time as the elongation of the stem and of the internodes and the connected development of leaves, which normally increase in size. This phase is responsible for the proper formation of the spike. Differentiation of flower organs ends with heading and flowering. Normally durum wheats are self-fertile, even though out-crossing can reach 5%, depending upon the variety and environmental conditions. Humid conditions are more favorable to selfing, whereas drier conditions favor out-crossing. At anthesis, anther filaments elongate rapidly and anthers release yellow pollen grains, first at the base and then at the apex. Thus, normally a large amount of pollen dusts the feathery stigmas of the same flower, and the remaining pollen is released outside the flower, into the air. The blooming of each spike lasts three to six days, depending upon the weather conditions. It begins in the lateral florets at the center of the head and proceeds toward the apex and the base of the spike and toward the central flowers of each spikelet. Once fertilized, the ovary rapidly increases in size, and the caryopsis develops. Two to three weeks from fertilization, the embryo is physiologically functional, able to develop into a new seedling. At the third week, the caryopsis is normally at the milky stage and still retains the chlorophyll synthesis. From this phase onward, the accumulation of reserve substances (starch and protein) rapidly increases the dry weight of the seed. This phase (from fertilization to ripening) lasts 3-7 weeks, depending on the genotype and the environmental conditions. In this phase, the economic yield is accumulated. Complete ripening is attained when the water content of the seed is below 15%. The ability to accumulate a high level of reserves during the last three weeks, particularly in conditions of water stress, is a genetically controlled trait of enormous importance in a large part of the area in which durum is cultivated.

■ SOILS AND CLIMATES SUITABLE FOR DURUM

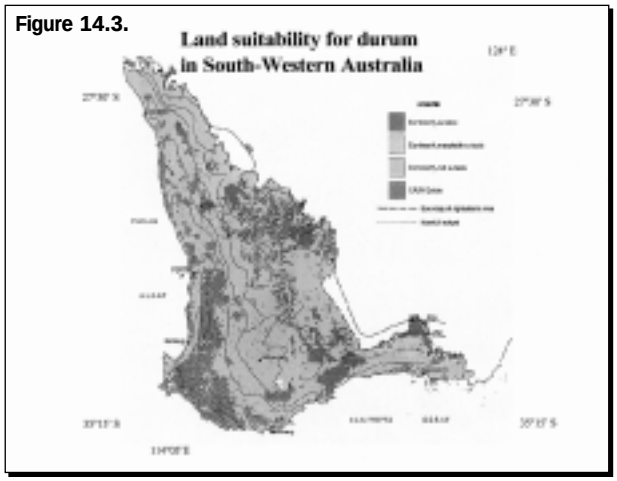
Durum evolved in the Mediterranean basin where the soils are mainly alkaline clays and clay loams and the climate has wet winters and dry summers. The main production areas in the world have climates that range from moderate rainfall (more than 350 mm annually) with low winter temperatures, to low rainfall (less than 350 mm annually) with mild winter temperatures and various combinations of these. Durum has not so far been widely adapted for winter sowing in summer dominant rainfall areas, or to acidic soils. The performance of durum relative to bread wheat on soils with pH less than 6 is extremely poor (see Table 14.6); grain yield and protein percentage are very low and there is no advantage for durum over bread wheat.

Table 14.6 – Yield of durum relative to bread wheat on acidic soils in Western Australia

Site and year		Percentage of bread wheat grain yield	Average grain yield (t/ha)
1993	Wongan Hills	71	2.69
1995	Nabawa	80	2.14
1996	Nabawa	65	1.04
Mean		72	1.96

On clay loam soils with neutral or alkaline pH (see Table 14.7), conditions are more suitable for durum in Western Australia. Durum yielded almost as much as bread wheat at yield levels ranging from less than 1t/ha to over 3t/ha in the low and medium rainfall zones.

Figure 14.3.



Land suitability for durum in South-Western Australia.

Table 14.7 – Yield of durum relative to bread wheat on clay loam soils with neutral to alkaline pH in Western Australia, 1992-1996.

Site and year		Percentage of bread wheat yield[1]	Average yield of best 5 durum (t/ha)
1992	Merredin	97	1.79
1992	Wilgoyne	98	1.62
1993	Merredin	75	1.89
1993	Wilgoyne[2]	82	0.6
1995	Merredin	100	2.45
1995	Wilgoyne	88	1.94
1995	York[3]	121	3.54
1996	Merredin	90	2.22
1996	Wilgoyne	88	1.76
1996	York	101	2.52
Mean		94	2.03

[1] Best five durum as percentage of best five bread wheat
[2] Frosted
[3] Leaf rust

The clay and clay loam soils with neutral or alkaline pH and with the absence of boron or aluminum toxicity were considered the most suitable soil characteristics. According to our estimation there are over 3 million hectares that meet the durum wheat requirements in the South Western Australia (Table 14.8). Given constraints of rotation, suitability of terrain and grower adoption, we anticipate that at least 0.5 million tonnes of durum could be produced annually when the industry matures. Our recent testing of locally available durum lines has shown that several are extremely tolerant of boron toxicity. This could open up another 1 million hectares of land that is otherwise suitable. In addition, our circumstantial evidence points to the possibility that durum is sensitive to aluminum toxicity, not to low pH per se, and this would also enlarge the available area. Our estimate of 0.5 million tonnes as a potential production thus appears conservative.

Table 14.8 – Hectares of soil per suitability class. • includes CALM land • climatic factors not considered

1 Agricultural area		
Class 1 (suitable)	3.2 million ha	12%
Class 2 (marginally suitable	1.1 million ha	4%
Class 3 (unsuitable)	22.6 million ha	84%
2 Zone of Ancient Drainage		
Class 1 (suitable)	1.8 million ha	19%
Class 2 (marginally suitable)	0 million ha	0%
Class 3 (unsuitable)	7.6 million ha	81%

VARIETIES AND VARIETAL IMPROVEMENT

In most production areas in the world where durum improvement has been active (e.g. Italy), durum cultivars yield about the same as varieties of bread wheat. In Western Australia, where research is in its infancy, durum cultivars so far yield less than bread wheat. This is not surprising since the varieties and breeding lines so far tested were bred for conditions in eastern Australia where the soils are inherently more fertile and there is a summer incidence of rainfall. Climatic conditions of South-Western Australia are more similar to the drier, Mediterranean regions where durum has been grown at rainfall of less than 400 mm with a winter incidence and a dry grain filling period. We assume that grain yield and quality advances are most likely to come from germplasm well adapted to the drier, Mediterranean regions.

The four durum varieties currently available in Australia are Kamilaroi, Wollaroi, Yallaroi and Tamaroi. All have suitable grain quality for both domestic and export markets. They are mid to short season, semi-dwarf types (between Amery and Carnamah in maturity). In Western Australia none are suitable for sowing before mid-May or after mid-June.

Wollaroi is a short-season variety, suitable for early June sowing and probably better adapted to drier areas. Kamilaroi, Yallaroi and Tamaroi are slightly longer season varieties suited to late May sowings.

Dr. Ray Hare of the National Durum Wheat Improvement Programme (NDWIP) bred the Australian durum varieties at Tamworth in New South Wales. They are all resistant to the three rusts and moderately resistant to Septoria tritici. They are all susceptible to crown rot. However, Wollaroi has shown a certain level of tolerance to Boron toxicity in laboratory tests. Yallaroi, Wollaroi and Tamaroi are moderately resistant to cereal cyst nematode and root lesion nematodes. Wollaroi and Tamaroi have shown a good resistance to pre-harvest sprouting damage by current standards in Western Australia. The Australian durum varieties have no vernalization response and are photoperiod insensitive.

■ PESTS AND DISEASES

Durum is susceptible to the same range of pests and diseases as bread wheat. Of the several hundred described diseases of wheat, less than 50 are of probable economic importance in durum. Diseases discussed in this chapter are only the diseases relevant for Australia and Western Australia in particular. In Western Australia the most troublesome diseases are expected to be crown and root rots, black point and Barley Yellow Dwarf Virus (BYDV). Among the other pests that we anticipate could be important are aphids (especially in their role as transmitters of viruses) and nematodes.

Crown rot

Crown rot (*Fusarium graminearum*) is a soil-borne disease, which is limiting the growth of durum and expansion of the durum industry in Australia. The level of resistance to crown rot in durum is generally less than in bread wheat. Durum can be devastated by crown rot. Yield losses from crown rot are caused by sterility of the florets. The crop symptoms are usually observed after flowering when scattered white-heads develop in a crop. Death of plants or tillers after heading is evident in infected fields. Stem bases are honey colour and soft; under moist conditions stem bases and lower leaf sheaths are covered by cottony pink mycelium. Heads of these plants may be empty or partially filled. Crown rot can be confused with take-all, which also causes white-heads, but is caused by different fungi. Crown rot can result in grain losses of 50% or higher in durum where the season and rotation have allowed the disease to build up. Extremely high yield losses from this disease have been recorded in recent years. In 1990, a yield loss of 50% was recorded in Kamilaroi in Malu, Queensland (Wildermuth, pers. comm.). In 1997, yield losses up to 40% were detected in durum in Merredin, Western Australia.

Australian durum varieties are extremely susceptible to crown rot, but improved disease resistances can be expected in future durum varieties. However, crop rotation can be the most important management tool to reduce losses from crown rot. Fusarium survives predominantly in infected stubble residues where it may persist for more than a year. It is recommended that a durum variety should not be planted in an area where crown rot was present in the previous two years. Where crown rot has occurred, the rotation should be lengthened and include non-host crops such as pulses, canola, or else a grass-free pasture or fallow. Oats will provide an effective break in most situations. A three-year break from host crops may be required where disease levels are high or where susceptible bread wheat or durum has to be sown. Control of grass weeds in non-host crops and fallow is essential. Cultivation of soils, where possible, also aids the decomposition of infected stubble and will help reduce disease levels. Rotation to any non-cereal crop lessens the level of the fungus in the soil and thereby reduces the level of disease in succeeding durum crops. Adequate nitrogen and potassium levels appear to reduce the severity of the disease, probably because the plants are more vigorous and therefore less affected by the pathogen. On the other hand, excessive fertility, especially excessive levels of nitrogen, increases the severity of the disease. Ammonium nitrogen sources appear to reduce the severity of Fusarium spp. relative to nitrate nitrogen. In Italy, the farmers having problems with crown rot use Guazatine seed dressing with very successful results.

Black point

The cause of black point is uncertain. It has been associated with the fungus *Alternaria alternata* and with enzymes produced by the seed (poly phenol oxidase, ppo) both of which are favor by humid conditions. Black point is very undesirable in durum where it may alter the color of the kernel, adding undesirable black specks in semolina It is a problem in durum deliveries particularly in wet areas and may cause considerable downgrading when conditions favor its development. Humidity and temperature have a major influence on black point development and varieties differ in their susceptibility. However, the Australian durum varieties should provide sufficient protection to prevent significant downgrading of grain following wet periods after flowering.

Yellow leaf spot

Yellow leaf spot (*Pyrenophora tritici-repentis*) survives in wheat residues. Resistant varieties are the best way to control yellow leaf spot. Symptoms are typically small, dark spots containing small, dark sites of infection surrounded by a variable sized yellow border which may cover much of the leaf. The disease is promoted by minimum tillage and mono-culture, which increases inoculum produced in wheat stubble. Crop rotation with non-hosts is advised. In a recent study, increasing soil nitrogen and using nitrapyrin (which keeps nitrogen in the ammonium form) reduced yellow spot. Fungicides such as mancozeb reduce spotting but are economically questionable in many areas. Recently, it has been noticed that bacteria protected wheat foliage from yellow spot. Resistance to yellow spot has been detected in several durum selections and incorporated into Australian durum varieties. Wollaroi and Tamaroi have consistently exhibited intermediate resistance to yellow leaf spot.

Septoria nodorum blotch

This disease occurs throughout the wheat belt, particularly in high rainfall areas, and is most damaging in warm moist conditions. However, in Western Australia information about this disease is not available at the present time because durum is mainly concentrated in medium to low rainfall areas where the incidence of this disease is limited. To control *S. nodorum* it is advisable to rotate with host free crops or manipulated pasture. Avoid

■ PESTS AND DISEASES *(continued)*

early sowing where the climatic conditions are favorable for the pathogen. Fungicide spray, such as Tilt may be economical only with crops expected to yield above 3t/ha and should be applied after the flag leaf has emerged.

Rhizoctonia bare patch

Rhizoctonia bare patch (*Rhizoctonia solani*) information not available for durum.

Root lesion nematode

Root lesion nematode (RLN) is caused by Pratylenchus thornei to which durum has adequate resistance, and by *Pratylenchus neglectus* to which the current durum cultivars have little resistance.

Rusts

Seedling and adult plant tests have indicated that the Australian durum varieties have adequate resistance to stem rust (*Puccinia graminis*), leaf rust (*Puccinia recondita*) and stripe rust (*Puccinia striiformis*). The level of resistance to the three rusts is better than in the bread wheats in WA. The improved resistance of the durum varieties to leaf rust is exemplified by the results at York in 1995 in the presence of a local epidemic of leaf rust, where the durum out yielded the bread wheats by 20%.

The Australian durum cultivars are immune to flag smut (*Urocystis agropyri*) and stinking bunt (*Tilletia tritici*).

Viruses

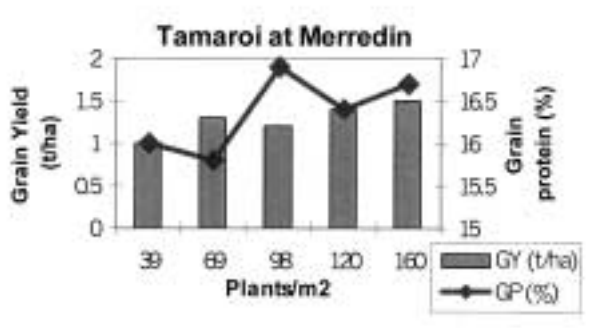
Not under satisfactory control.

■ AGRONOMY, ROTATION AND NUTRITION

The durum varieties available to Western Australian growers are short and mid-season types that are best sown from mid-May to mid-June in most parts of the grain belt.

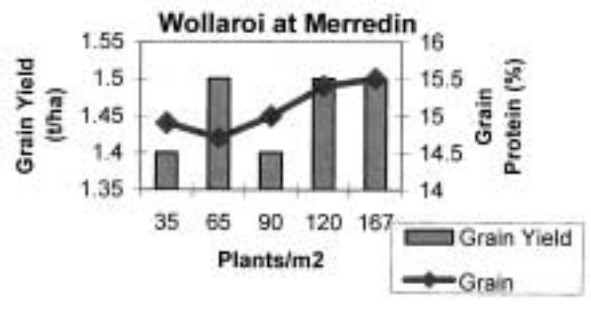
Research to date has shown that the optimum plant population for durum is about the same as bread wheat. Seed rates can be 5 to 10 % higher than for the bread wheats as the kernel size is mostly larger and most durums have lower tillering capacity than bread wheats. Typical yield responses to plant density are shown in figure 14.4 and 14.5.

Figure 14.4.



Tamaroi at Merredin.

Figure 14.5.



Wollaroi at Merredin.

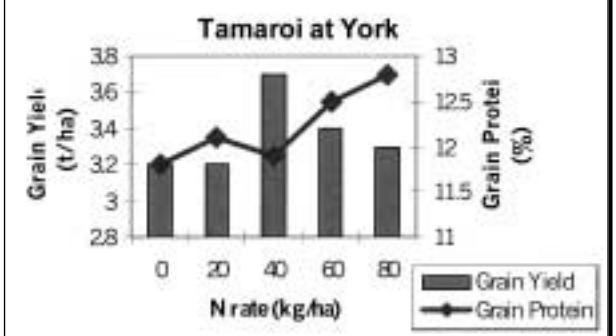
Research now underway will clarify this situation. Seed should be sown at about 2 to 3 cm depth because of the short to medium coleoptile lengths of the available durum varieties.

Ensure seed is free from contamination with bread wheat and other cereals. When buying seed check the source for purity, plumpness and a high germination percentage.

Durum has lower seedling vigour than bread wheat resulting in weak weed competitiveness in the early stages of growth. Effective weed control in the early stages is necessary to avoid a yield penalty. Use recommended herbicide rates and apply at the correct times to avoid chemical damage.

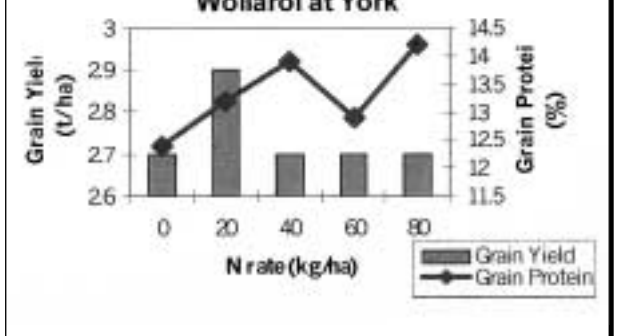
Rotation is extremely important for disease management, control of weeds and for increasing soil nitrogen. If a good legume rotation is practised (at least two years in the last five years of high quality (more than 50%) legume pasture or three years in the last five of grain legumes), then the crop seldom responds to nitrogen fertilizers (see Figure 14.6 and 14.7). Furthermore, it increases grain protein substantially if compared to durum following wheat. However, an application of nitrogen at seeding is advisable to ensure that grain proteins are high.

Figure 14.6.



Tamaroi at York.

Figure 14.7.



Wollaroi at York

The rotation strategy should also include measures to reduce grass weeds in the years leading up to the durum crop. Pasture manipulation, heavy grazing with sheep and spray topping can be used in the pasture phase and different combinations of chemicals can be used in the previous non-cereal crops. Plan to avoid inducing herbicide resistance in grasses.

Rotation with non-cereal crops is also beneficial in controlling both root and leaf spot diseases of the durum crop. Green manure cropping with legumes may be used to boost grain proteins. It is also a valid tool to control weeds and diseases in some situations.

Fertilizer rates should be determined based on yields and paddock histories. Apply phosphate and potassium

■ AGRONOMY, ROTATION AND NUTRITION *(continued)*

according to the soil test. As a guideline, apply nitrogen at sowing and/or up to 4 weeks after sowing, at about 25 kg/ha for each tonne of expected yield in nitrogen-responsive situations. Durums are known to be sensitive to deficiencies of zinc, manganese and iron. If these elements have not been applied recently to deficient soils they should be re-applied before the durum crop. Tissue testing is often a good guide to deficiencies. Durum is sensitive to toxicity of boron (>5mg/kg in $CaCl_2$). However, Wollaroi has shown a very good degree of tolerance to B toxicity using a modified lab screening technique and should be used where soil tests indicate B toxicity is a problem. Durum is extremely intolerant of Aluminum toxicity. Avoid soils where the soil test indicates Aluminum level higher than 10mg/kg (in $CaCl_2$).

HERBICIDE TOLERANCE

Good agronomy for durum demands a grass free site. A grass free pasture and a grass free legume crop are the most effective ways to achieve these conditions.

Limited data from testing at 3 sites in 1998 only have demonstrated variable and sometimes confusing responses in the 2 most common durum cultivars, Tamaroi and Wollaroi. The safest options based on these limited data are:

- Tigrex and Jaguar appear safe at label rates
- Diuron and MCPA Amine should be used with similar cautions as in bread wheat
- Group B herbicides are suspect for use on durum
- 2,4-D Amine and Barrel are probably acceptable for use on durum

Avoid unusual or multi-chemical tank mixes that may contain oils and/or wetters as they may increase crop phytotoxicity.

If the season is too short with a sharp finish the chemical effect on Tamaroi maybe magnified since it is a longer season variety than Wollaroi and may not have time to compensate for any retardation by a herbicide.

■ THE ECONOMICS OF GROWING DURUM

If durum is to find a place in the Western Australian farming system, growers must be attracted to both the potential financial returns and the feasibility of production including its culture and marketing.

Samples collected from commercial durum crops in the 1997/98 season were put through a simple economic analysis (J. Henderson) to give some indication of the profitability and viability of introducing durum into Western Australian farm rotations (Table 14.9).

Table 14.9. Grain yield, protein percentage and gross margin of durum compared to bread wheat crops in WA in 1997/98.

	Yield (t/ha)	Protein (%)	Gross Margin
			($/ha)
ADR1 (13)	1.60	13.92%	$207.00
ADR2 (8)	2.20	12.46%	$295.57
ADR3 (16)	2.22	10.37%	$246.10
ASW (9)	2.66	9.51%	$232.65
APW (6)	2.51	10.55%	$249.37
AH1 (6)	2.34	12.26%	$239.88
ADR1 (5)*	2.07	13.51%	$317.87

* Durum 1 after removing cases heavily affected by frost and crown rot

The economic analysis showed that out of the 13 cases meeting the ADR1 (13% protein) segregation, 8 cases suffered yield loss due to severe frost damage and crown rot. Therefore the average grain yield and consequently the gross margin for the ADR1 segregation fell below that of ADR2 (11.5% protein).

After removing the cases that suffered yield loss due to these factors the average grain yield of the remaining cases in the ADR1 segregation was 2.1 t/ha at 13.5% grain protein with a gross margin of $317.87.

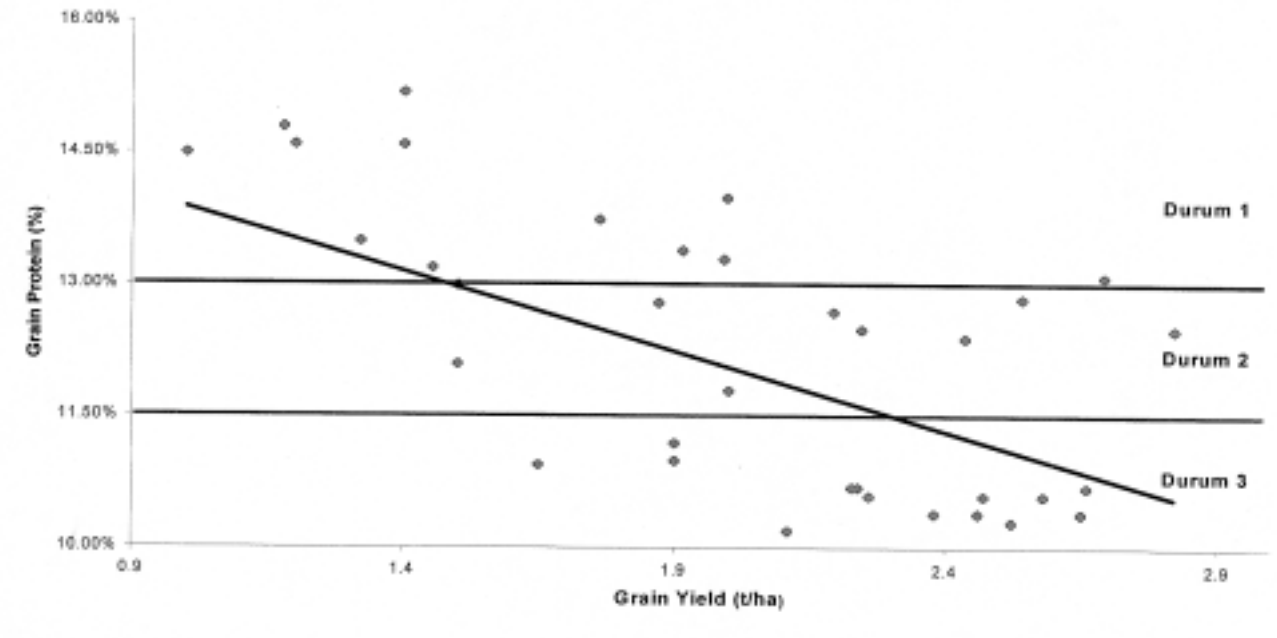
Two key messages were identified from growers experience in 1997/98:

- Durum wheat can achieve high returns for growers in Western Australia;
- Good agronomic management is essential for a profitable crop.

In the 1997/98 season in Western Australia, about 50 farmers harvested approximately 3,000 tonnes of durum, of which around 1,000 tonnes was delivered for sale while the rest was kept as seed by the farmers for the coming season. In Western Australia, up to 20,000 hectares are expected to be grown in 1999 with 100,000 tonnes produced annually by 2002. Prices for durum are buoyant and the long-term prognosis for pasta consumption worldwide is optimistic.

The Scattergram below (Figure 14.8) shows the trend of grain yield versus grain protein for the durum. While the graph does show a clear downward trend in protein as the yield increases it also shows that it is possible to achieve higher yields and high protein (to meet ADR1 segregation) if conditions are correct for durum and there is an absence of disease.

Figure 14.8.



Scattergram of grain yield vs grain protein.

HARVESTING AND ADMIXTURES

Because of its hard texture, durum may fracture if over threshed. Adjust concaves to avoid excessive cracked grain or embryo damage.

Durum grain should not be mixed with other cereals during harvesting, storing, transport or sowing. A mixture with other grains severely reduces the quality of durum semolina for pasta. Durum grain must be strictly segregated, on-farm storage is necessary if immediate delivery cannot be arranged.

PLACE OF DURUM IN THE FARMING SYSTEM

Durum is a specialty crop that needs higher levels of management than bread wheat. It will not fit into all farming systems in the Western Australian grain growing areas.

A survey of the soil types thought to be suitable for durum has shown that the best soils are not concentrated into large, homogeneous areas but they are scattered from north to south, mostly in the low to medium rainfall areas of the grain belt. We anticipate that there will be fewer problems on average with black point and leaf diseases in the lower rainfall areas. There are a few areas in the high rainfall zone that may prove suitable with appropriate management (e.g. Avon and Chapman valleys). On balance we anticipate that the bulk of the durum wheat industry will develop on the heavier soil types in the low to medium rainfall areas of Western Australia.

Interest in durum from grain growers in this State has built up over the past few years and is now widespread. This interest is due to high prices relative to bread wheat, by the need for alternative crops for particular farming systems, and the need to reduce risks and increase profits.

■ ACKNOWLEDGMENTS

We acknowledge Mr. Frank Boetel for his valuable assistance in management of most of the experimental data reported here; the collaboration of Dr. Wal Anderson, co-supervisor of the durum wheat project for the western region; Mr. Jamie Henderson, for the economic analysis; Mr. Terry Piper and Mr. Craig Pensini for their contribution in the herbicides sensitivity trials. We also acknowledge the contribution of the GRDC and local, innovative growers towards the establishment of the durum industry in Western Australia.

FURTHER READING

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FEED WHEATS – A FUTURE MARKET FOR WESTERN AUSTRALIAN GRAIN GROWERS

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Introduction

Wheat is an excellent feed grain for most livestock species even though it has been primarily produced as a grain for human consumption. Traditionally we have referred to feed wheat as that which either did not meet the quality standards for the human market or when its supply exceeded the requirements for the same market. While there will always be a proportion of wheat still marketed to the animal feed industry in this way, the development of specific varieties of wheat for the animal feed industry has begun.

This chapter will outline the major requirements of the stockfeed industry, and attempt to predict the possible market for wheat in regard to the Western Australia industry.

The stockfeed industry

A considerable proportion of Australia's cereal grain and grain legumes are consumed by animal industries. Traditionally this has been the pig and poultry industry, but in recent years there has been a large increase in demand for feed grains for feeding beef cattle in feedlots and for dairy cows. In less than 10 years, demand for wheat by the Australian feed industry has increased by 30% (Table 14.10). The 2.2 million tonnes of wheat required by the Australian feed industry is still small however compared to the 526 million tonnes of total feed manufactured on the world market in 1993 (Feed Grains Study, 1995).

The Australian dairy and beef industries have shown the fastest growth in production over recent years (averaging in excess of 10%), with more intensive industries experiencing steady but low growth (2-3%). Feed grain usage varies significantly between sectors. Wheat is the most widely used grain due to its widespread availability and relatively high content of energy. It is used as a key ingredient in broiler, layer and pig diets. Since there is not expected to be any substantial leap in consumption of meat in Australia, any substantial growth in the future will be driven by export markets for both meat products and feed grains.

Table 14.10 – Use of wheat (kt) in Australia by the feed industry for 1992/93, that predicted for 1999/2000 and the proportion of total feed grain that is wheat for each sector

Sector	1992/93	1999/001	% of total feed grain used by each sector
Poultry meat	532	646	37
Pigs	511	562	31
Layer hens and pullets	197	195	38
Beef cattle	233	333	12
Dairy	135	317	15
Miscellaneous	99	167	N.A.
TOTAL	1,707	2,220	

[1] predicted value based on previous use and projected change in animal numbers

USE OF WHEAT IN ANIMAL FEEDS

Any feedstuff will be used in diets for animals if it supplies the required nutrients, it is cost competitive with other available ingredients, and the user is confident that it will produce the desired result. While in the past, animal industries may have used wheat considered unsuitable for other purposes, such as weather-damaged grains, this is no longer the case. Far greater attention is being given to the effect that poor quality grains will have on animal performance and quality of the end product. The feed industry is now very sophisticated, and since the cost of feeds commonly represents 60 to 70% of the total cost of production for many enterprises, every effort is being made to reduce the cost of the mixed diet whilst meeting dietary specifications.

WINTER WHEAT

40% of Australian agriculture is carried out in the high rainfall zones, where grazing enterprises predominate and these are vulnerable to income fluctuations associated with volatile meat and wool markets. The option of growing wheat in these areas has, consequently, the potential for some producers to diversify via a high yielding grain crop.

A winter wheat (sometimes referred to as red wheats) are those that are sown around the time of the autumn break, remain vegetative through the cold wet winter and then flower around the middle of November. Due to the relatively late flowering, the risk of damage from frosts is lower than for conventional wheat varieties. They are well adapted to areas with good rains in April and reliable spring rains through until at least late November, such as southern Victoria but also small areas in the south west of Western Australia. To approach the potential of over 5 tonnes per hectare, the crop requires a well structured, well drained paddock and a very high standard of management.

Lawson and Paterson are the two varieties released under licence to the Australian Wheat Board. Declic and More are two other varieties that have been grown in Victoria.

Based on the results of experiments conducted by Dr Ray King at the Victorian Institute of Animal Science, the digestibility of red wheat was essentially the same as Australian Standard White (ASW), with digestible energy content estimated at about 14.3 MJ/kg. Average crude protein was about 11%, however crude protein can be expected to vary in a similar manner to ASW, depending on the season and agronomic variables such as fertiliser.

Provided there is sufficient soil moisture for these varieties to be sown early (e.g. before the end of March), they can respond well to grazing during winter and then recover to produce a high yielding wheat crop. If the crop is intended for grain only, April or May sowings are usually ideal. Long season winter wheats flower several weeks later than any Australian spring wheat bred for the wheatbelt and they also require low winter temperatures before flowering. Hence they are only likely to be suited to a small area of the south west in Western Australia, but these are areas where few options for growing cereals currently exist.

QUALITY OF FEED WHEAT

There appears to have been scant attention by the grain industry in the past to the specific needs of the feed industries. One reason may be that the feed industry has been relatively indiscriminating in their requirements for feed grain. They have been relatively undemanding but constant customers.

The prime nutritional constraints in specific diets are those parameters which have the greatest cost pressure against them. The magnitude of these pressures varies with the specifications nominated, and the nutrient composition and cost of alternative materials available. This will be different for each animal species and with the range of diets used within a species, consequently these constraints tend to be a moving target.

Table 15.11 indicates the value of wheat in a pig grower diet varying the level of crude protein. On average, the value of wheat changes by approximately $2.70% of crude protein. Given that the average energy content of wheat is 14.4 MJ digestible energy / kg, the value of wheat would increase by $24.88 per 10% shift ($17.27 per MJ), compared to $3.01% shift in crude protein. This reflects the relative importance of wheat as a source of energy rather than protein in the diet of most animals.

Table 14.11 – The value of wheat in pig grower diets when crude protein is changed

% crude protein	$/tonne
7	148.43
8	151.95
9	153.94
10	156.98
11	160.00
12	162.54
13	164.53
14	168.05
15	170.13

Variability in nutrient values for wheat

Parameter	Range
Crude protein (%)	7 – 17
Bushel weight (Kg/Hl)	45-85
Metabolisable energy (MJ/kg)	11.03 – 14.57
Digestible energy (MJ/kg)	12.90 – 15.00

To date there has been little payment for quality in relation to nutritional factors. Currently specifications relate to issues such as residues, weight and admixture although recently crude protein has been included. In the future, purchasers will move towards a basis of energy and protein, but this is currently difficult due to not being able to test for these rapidly and reliably at the point of receival. The critical quality factors sought are consistency, free of weeds, mould, moisture and pests. Protein is emerging as a quality factor and in the future the feed industry will pay a premium for high protein grain. It is more difficult to pay for energy, because it currently cannot be measured on receival. Effective marketing, infrastructure and quality systems will enhance demand for feed grains such as wheat and the prices paid to producers.

FUTURE CONSIDERATIONS

In general there has been a lack of communication and co-operation between the grain and the feed industries. The call by the feed industry in the Eastern States during recent droughts to permit the import of feed grains from overseas was counteracted by the grains industry that argued that this could result in the introduction of new plant diseases and pests. This was a clear signal that both groups needed to have a better understanding of each other's needs and concerns.

For grain growers to be attracted to the production of wheat specifically for animals, there must be rapid and accurate procedures for establishing the nutritional value of grain for the different livestock enterprises, so that the prices paid will reflect the grain value in terms of animal performance. Similarly, animal industries will benefit from the precise knowledge of the nutritional value of the grains, as well as the improvements that can be made through processing and storage procedures. The rational marketing of feed grains could then be achieved, with the benefits from more efficient animal production being shared between the grain grower and animal producer.

REFERENCES

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■ TRITICALE

Ron McTaggart

Triticale (*x Triticosecale Wittmack*) is a cereal derived from wheat and cereal rye. It is a quality feed grain with increasing use in Australia's animal industries. The value of triticale in human nutrition has been poorly explored despite the high level of dietary fibre compared to wheat. The yield and quality of triticale has risen and it is replacing other cereals as a fodder and grain plant in New South Wales on acid soils.

Early triticales were very tall and resembled cereal rye in form. Backcrossing to wheat has led to plumper grains and higher yields. The plant is taller than most wheats and the flowering spike has awns. The inflorescence has a narrower outline than wheat due to the grain shape of triticale. The grain is longer and narrower than wheat and its colour is light brown. The plant does not tiller as much as wheat and seeding rates should be higher than wheat to achieve the same number of heads/metre^2 at harvest.

HISTORY

The first cross between wheat and rye was reported as long ago as 1857. The cross was a sterile plant. A number of successful wheat x hybrids appeared in Russia in 1918. The F1 plants produced seeds which bred true. The name triticale appeared in Germany from wheat (*Triticum*) and rye (*Secale*) about 1935. Today's triticale varieties are due to progress made by scientists in Canada, Poland, United States and Mexico. During its short life history in commercial production the features of the crop have changed. The International Centre for Maize and Wheat (CIMMYT) in Mexico began breeding work on triticale in 1965. The triticale varieties of that time were tall, late maturing, sometimes sterile, and the grain was small and shrivelled. Australia has a coordinated Triticale Improvement Program with three breeding centres – University of New England, University of Sydney, and University of Adelaide. Triticale types are selected for fodder types or for quality grain production.

■ SOIL TYPES AND RAINFALL

Triticale has been favoured on soils of low fertility perceived to be unsuitable for wheat. The reliability of triticale in marginal soils is due to its early vigour, aggressive root development and ability to yield when extremes of pH and marginal trace element status exist. The early vigour of the crop makes it the best-adapted cereal for soils that become too wet during the growing season.

Triticale can be grown in rainfall zones from 200mm to 1200mm.The new triticale varieties will out-yield wheat in the high rainfall zones which provide a long grain filling period. Like all cereal crops, paddock selection and root disease control are important for high yields.

AGRONOMIC TRAITS

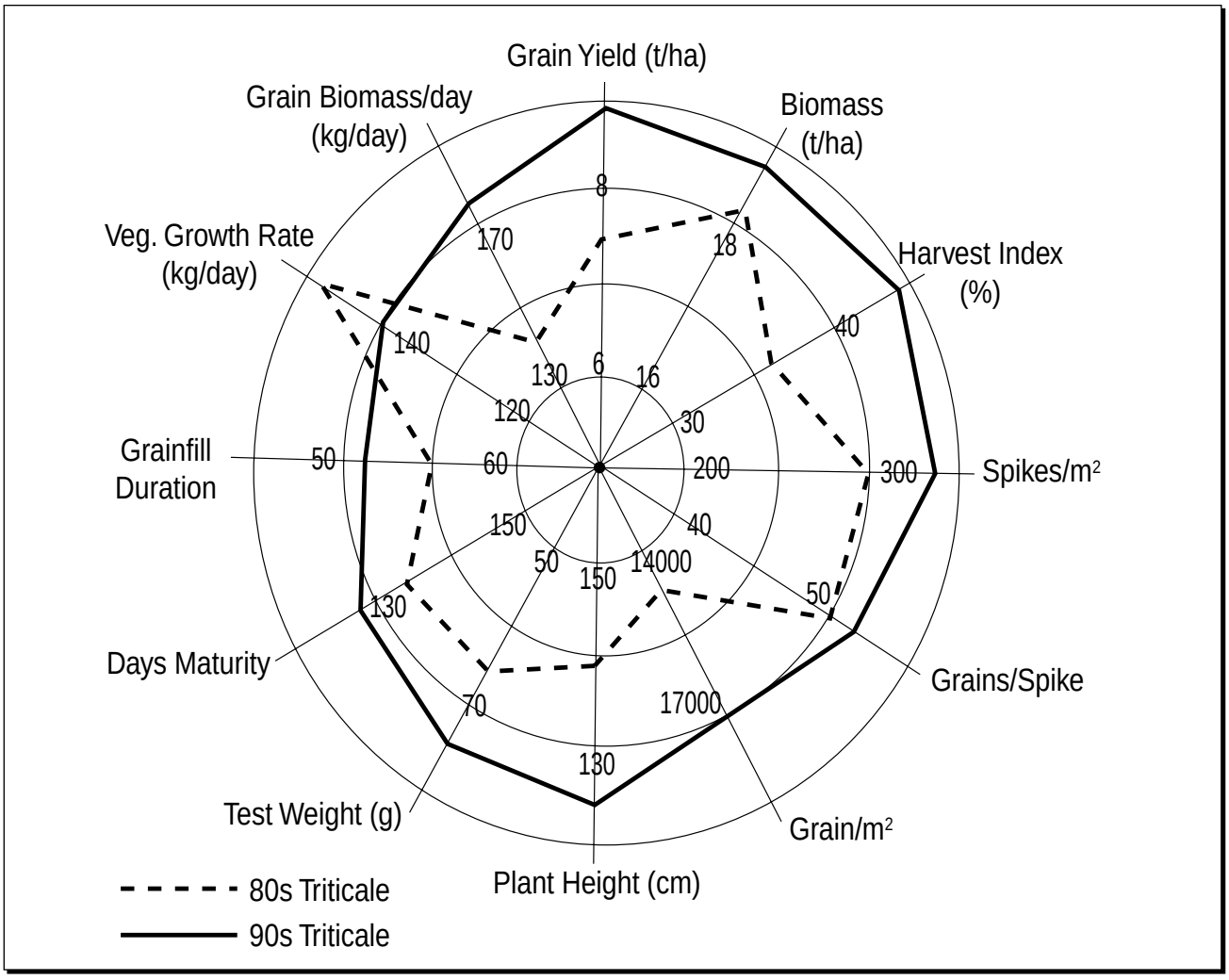
Early problems with triticale included excessive height, low head fertility, low hectolitre weight, shrivelled grain and late maturity. Breeding and selection have fixed many of these problems.

The diagram below shows the changes which have taken place in the last ten years in grain type triticale.

Cereal Foods World, June 1996. American Association of Cereal Chemists

Triticale has a larger grain than wheat and seeding rates should be higher than wheat. The early vigour of triticale, when it is combined with high seeding rates provides good competition against weeds. Seeding rates vary with rainfall and yield potential.

Figure 14.19 – Changes to grain type triticale.



SEEDING RATE

Table 14.12 – Seeding Rate

Annual Rainfall mm	Target Plant Density (plants /m^2)	Seeding Rate kg/ha *
250-300	160-180	95-110
300-450	180-200	110-120
450-500	200-220	120-130
>500	240	130-140

*(Based on 1000 grain weight of 48 grams and 80% establishment.)

Triticale should be sown at the same time as wheat. It may flower 10 days earlier than wheat but grain filling takes longer. Test weight and plump grain depend on cool spring conditions so early sowing is important.

Triticale has similar tolerance levels as wheat to the same groups of herbicides. Modern varieties of triticale have leaf disease tolerance especially to stem, stripe and leaf rusts.

Long season triticales are used for grazing or fodder production. They are sown on the opening rains; grazed during winter and then saved for hay or silage. Their grain is usually smaller and lighter than the spring types, which are grown for grain only.

VARIETIES

Fodder types (Tall, late maturing, high biomass production – Maiden, Madonna

Supeseded varieties – Satu, Coorong, Currency, Tyalla.

Long season

Abacus – must be planted early for 7 months season to fill grain.

Standard mid season

Tahara – the most widely grown variety in 1990s. It is fully resistant to Cereal Cyst Nematode. It has weak straw and will lodge when yields are over 3 tonnes.

Medium Season

Muir – has a good straw strength and hectolitre weight and is well suited to high rainfall areas – >600mm

Credit – resistant to stem, stripe, and leaf rust. It is not Cereal Cyst Nematode resistant but is a high yielding variety with good hectolitre weight.

Everest – high hectolitre weight, high yielding. Expect 10 per cent better than Tahara in 500mm rainfall.

Treat – a medium season variety maturing 6 days earlier than Tahara with superior straw strength and hectolitre weight (5kg better than Tahara).Average yield will be 2-3% better than Tahara but 10-15% better in high yielding sites.

DELIVERY STANDARDS

Variety selection, paddock selection, time of planting and good finish all play a part in producing high yielding, good quality grain. Delivery standards for triticale may vary but moisture is expected to be below 12.5%, screenings below 6% and test weight above 65kg/hectolitre. Discounts may apply for triticale with screenings to 15% and test weight down to 60kg/hectolitre

There is no segregation for varieties but other delivery standards exist for staining, sprouting and weed seed, or insects in the sample.

FEED QUALITY

Test weight is used as the first measure of grain quality but this should be backed up by laboratory tests for metabolisable energy and protein. Changes made to varieties in the last 10-15 years have produced smooth grain and with high energy levels. Triticale has a superior amino acid balance for animal feed rations.

Triticale quality has changed and data from animal trials done with the old varieties do not have relevance for today's producers. There will always be variation in quality from paddock to paddock and season to season. The following table is therefore only a guide to relativity between wheat, triticale and rye.

The high sugar level in modern triticales leads to increased palatability for cattle and reduces the "shy feeder" problem in dairy cattle and beef cattle in feed lots.

Processing

Low gluten content, inferior gluten strength and high levels of alpha-amylase cause triticale flours to form weak dough making them unsuitable for bread making. There is variability in the flour and triticale can be used as a partial replacement of wheat flours. Triticale can be used to make biscuits and cakes. Some work has been done in the US and Canada to compare malting quality of triticale with US barley. It was found that triticale had higher malt extract, higher diastatic power, and higher alpha and beta-amylase activity than barley – all factors of high malt value. Beers made were darker than from barley but the taste was acceptable. Advances in breeding have shown the current triticales to be suitable for many end-uses beyond just animal feed. Breeding continues to target traits for both human and animal consumption.

Pricing

Growing production has meant much more reliance on triticale by livestock producers. Its energy levels and improved palatability place it above feed barley by $12 – $15/tonne and $20/tonne below ASW price. Pricing should be based on laboratory analysis, and any grower selling triticale to livestock farmers would do well to sample and test the grain, and base the asking price on the analysis results.

Table 14.13 – International Triticale Screening Nursery – Proportion of varieties reaching high-test weight and flour yield.

Year of Testing	Test weight > 77kg/hl	Flour Yield > 70%
1977-78	2.0	1.6
1983-84	14.7	16
1988-89	46.2	35
1990-91	64.1	70.0

Ref – Cereal Foods World July 1996

Table 14.14 – Composition on a dry weight basis (%).

Cereal	Protein	Starch	Crude Fibre	Free Sugars	Ash
Triticale	10.3-15.6	57-65	3.1-4.5	3.7-5.2	1.4-2.0
Wheat	9.3-16.8	61-66	2.8-3.9	2.6-3.0	1.3-2.0
Rye	13.0-14.3	54.5	2.6	5.0	2.1

Ref – Cereal Foods World July 1996

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Sources:

Rainfall, maximum and minimum temperatures and from Bureau of Meteorology publications and are for varying lengths of record.

Radiation and evaporation are derived from AUSTCLIMEANWEEK, a database developed by CSIRO.

Units:

Rainfall (mm, monthly total)
Maximum and minimum temperature (°C)
Radiation (Megajoules per sq. m per day)
Evaporation (mm, monthly total)
M-O is May to October rainfall

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	M-O	Total
Albany														
Rainfall	34	28	45	76	132	140	156	137	107	80	42	31	752	1007
Maximum Temp	23.2	23.4	22.4	21.2	18.8	16.8	16.1	16.6	17.6	18.9	20.7	22.3		
Minimum Temp	14.7	14.9	14.1	12.5	10.4	8.8	8.0	8.2	9.1	10.2	12.1	13.6		
Radiation	24.5	22.1	18.8	14.5	11.0	9.4	10.0	12.2	16.8	20.7	23.5	25.1		
Evaporation	191	155	141	99	69	51	55	69	104	141	166	185	489	1426
Bencubbin														
Rainfall	14	21	24	23	38	52	46	38	21	16	13	13	211	319
Maximum Temp	34.5	33.5	30.9	25.4	20.5	17.1	16.1	17.5	20.7	24.8	28.6	32.3		
Minimum Temp	18.1	18.1	16.1	12.3	8.9	7.3	5.8	5.5	6.9	9.5	12.8	15.8		
Radiation	29.7	27.4	23.0	17.2	12.8	10.0	10.7	13.7	18.4	25.0	29.2	30.4		
Evaporation	342	285	252	162	107	73	83	102	142	213	262	320	719	2344
Beverley PO														
Rainfall	9	13	17	23	56	82	79	60	36	23	14	9	336	421
Maximum Temp	34.1	33.3	30.6	25.8	21.1	17.8	16.7	17.5	20.2	24.2	27.8	32.0		
Minimum Temp	16.3	16.7	14.7	10.9	7.7	6.0	5.2	4.9	5.5	7.8	11.1	14.3		
Radiation	29.8	27.3	22.5	16.3	12.0	9.5	10.5	12.8	15.7	22.7	28.1	30.4		
Evaporation	296	248	217	133	86	58	65	79	109	165	213	271	562	1939
Boyup Brook														
Rainfall	13	17	21	39	88	125	119	96	63	48	27	13	539	669
Maximum Temp	30.9	30.8	27.4	22.3	19.3	16.6	15.7	16.0	17.7	21.0	24.2	28.8		
Minimum Temp	12.8	13.7	11.2	8.5	6.2	5.0	5.0	4.2	4.8	6.8	8.7	11.3		
Radiation	27.5	25.0	19.8	14.1	10.3	8.6	9.3	11.6	15.5	20.8	25.1	27.8		
Evaporation	239	201	171	99	64	44	49	57	75	115	158	214	405	1487
Bridgetown PO														
Rainfall	14	14	27	46	111	151	148	123	87	65	32	19	685	837
Maximum Temp	29.7	29.6	27.1	23.2	19.0	16.6	15.7	16.5	18.3	20.5	24.2	27.5		
Minimum Temp	11.9	11.8	10.4	8.2	6.5	5.1	4.3	4.4	5.5	6.6	8.5	10.3		
Radiation	25.9	23.6	20.0	14.7	10.6	9.4	10.0	11.8	15.7	19.3	23.8	26.4		
Evaporation	231	196	166	94	61	42	46	54	70	107	151	206	381	1425
Brookton PO														
Rainfall	10	15	18	26	61	92	88	63	38	26	14	10	368	461
Maximum Temp	33.1	32.4	29.2	24.8	20.1	17.0	16.0	16.7	19.2	23.3	27.1	31.4		
Minimum Temp	15.1	15.7	13.9	10.6	7.2	5.4	4.5	4.5	5.0	7.1	10.5	13.4		
Radiation	29.2	26.5	21.6	14.9	11.0	8.9	10.0	12.0	15.9	22.0	27.5	30.4		
Evaporation	290	243	211	129	83	57	64	77	106	160	208	266	547	1894

APPENDIX I

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	M-O	Total
Carnamah														
Rainfall	11	15	21	23	51	82	70	54	28	18	11	9.1	303	384
Maximum Temp	35.9	35.5	32.7	27.3	22.3	18.9	17.7	19.0	22.1	25.7	29.8	33.4		
Minimum Temp	18.3	18.9	17.0	13.7	10.5	8.6	7.2	7.1	8.1	10.2	13.0	15.8		
Radiation	29.5	27.5	23.5	17.6	13.5	11.0	11.4	14.0	18.4	24.4	29.0	30.3		
Evaporation	337	290	259	163	108	71	78	99	136	203	253	309	694	2306
Chapman Res. Stn.														
Rainfall	7	12	14	22	63	105	95	64	35	22	10	6	384	455
Maximum Temp	34.2	34.2	32.1	28.3	23.3	19.7	18.5	19.3	22.0	25.0	28.9	31.9		
Minimum Temp	17.7	18.3	17.0	14.4	11.1	9.0	7.5	7.5	8.2	10.0	13.3	15.8		
Radiation	28.1	26.4	23.4	17.7	14.2	11.3	11.7	14.6	18.5	24.1	27.7	29.9		
Evaporation	345	303	275	176	119	78	83	108	146	213	261	314	746	2421
Corrigin PO														
Rainfall	11	17	22	23	49	65	62	49	30	23	16	13	278	380
Maximum Temp	32.5	31.4	28.8	23.8	19.3	16.2	15.2	16.2	19.0	22.7	26.6	30.3		
Minimum Temp	15.7	15.8	14.1	10.8	7.2	6.1	4.9	4.6	5.7	8.0	11.0	13.9		
Radiation	29.3	26.3	21.8	15.7	11.5	9.1	9.7	12.4	16.8	23.1	27.9	30.0		
Evaporation	302	250	217	136	88	61	70	84	116	175	222	280	594	2002
Cunderdin PO														
Rainfall	9	17	20	24	49	66	63	48	27	21	13	9	274	366
Maximum Temp	34.1	33.2	30.4	25.2	20.8	17.6	16.5	17.5	20.3	24.1	28.2	31.9		
Minimum Temp	17.6	17.7	16.0	12.8	9.2	7.7	6.3	6.1	7.3	9.6	12.7	15.5		
Radiation	29.2	26.3	21.8	16.0	11.9	9.4	10.0	12.5	16.6	22.8	27.3	29.5		
Evaporation	312	262	229	143	93	63	71	87	120	182	230	289	617	2082
Dalwallinu PO														
Rainfall	13	17	23	21	44	70	60	46	24	17	12	9	261	356
Maximum Temp	35.3	34.5	31.5	26.3	21.5	18.0	16.8	17.9	21.0	25.0	29.1	32.9		
Minimum Temp	18.4	18.5	16.6	13.2	10.0	8.0	6.5	6.6	7.8	10.2	13.2	16.1		
Radiation	29.7	27.5	23.5	17.7	13.4	10.3	11.0	14.0	18.8	24.9	29.1	30.4		
Evaporation	339	287	255	162	106	71	79	99	138	206	256	313	700	2313
Esperance MO														
Rainfall	14	27	25	48	77	80	98	88	55	50	39	17	448	618
Maximum Temp	26.2	26.4	25.2	23.1	20.2	17.9	17.1	17.7	19.2	21.1	22.9	24.8		
Minimum Temp	15.5	16.0	14.9	13.1	10.6	8.9	8.2	8.5	9.4	10.6	12.7	14.4		
Radiation														
Evaporation														
Esperance PO														
Rainfall	18	20	28	45	82	100	108	97	71	55	28	23	513	675
Maximum Temp	25.1	25.2	24.4	22.5	19.9	17.7	16.7	17.6	19.1	20.3	22.3	24.0		
Minimum Temp	15.5	15.7	14.7	12.2	10.0	8.4	7.3	7.6	8.7	10.2	12.3	14.1		
Radiation	23.4	21.7	18.2	13.9	10.6	9.1	9.7	12.4	16.5	20.1	22.6	23.9		
Evaporation	293	233	199	132	88	64	76	89	124	183	220	278	625	1981
Esperance Res. Stn.														
Rainfall	21	26	21	37	53	60	63	62	53	41	32	19	332	488
Maximum Temp	28.8	28.2	26.2	22.8	19.2	16.4	15.9	16.4	18.7	21.4	24.1	26.6		
Minimum Temp	14.0	14.7	13.4	11.3	8.9	7.0	6.2	6.4	7.4	8.7	10.8	12.3		
Radiation	25.9	23.6	20.1	15.2	11.1	9.2	9.9	12.4	16.4	21.2	25.0	27.6		
Evaporation	300	239	205	136	91	66	78	91	127	188	227	285	641	2033

APPENDIX I

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	M-O	Total
Geraldton														
Rainfall	28	11	19	24	68	118	96	63	31	19	7	4	395	489
Maximum Temp	22.8	29.5	28.7	26.9	23.5	21.0	19.9	20.6	21.9	23.3	25.9	27.8		
Minimum Temp	21.3	19.1	18.3	16.1	13.8	12.1	11.0	11.2	11.7	13.2	15.6	17.5		
Radiation	25.3	23.5	20.9	17.4	13.7	11.8	12.4	15.0	18.6	21.8	23.9	25.3		
Evaporation	246	188	181	139	102	78	81	101	128	166	188	208	656	1806
Goomalling														
Rainfall	10	14	17	24	48	71	64	50	26	21	11	11	280	367
Maximum Temp	33.7	33.8	30.1	24.8	21.1	17.8	16.8	17.1	19.9	24.1	28.3	32.4		
Minimum Temp	16.8	17.9	15.6	11.8	9.0	7.8	6.5	6.1	6.6	9.0	12.1	15.2		
Radiation	29.4	26.6	22.5	15.9	12.3	9.8	9.9	12.7	16.6	21.8	27.9	29.9		
Evaporation	316	267	235	146	95	64	71	88	121	183	233	291	622	2109
Hyden composite														
Rainfall	15	21	19	23	39	53	47	39	26	21	18	13	225	334
Maximum Temp	33.4	32.5	29.6	25.2	19.9	16.8	15.9	16.9	20.0	23.8	27.5	31.9		
Minimum Temp	15.4	15.6	13.9	10.8	7.1	5.6	4.6	4.6	5.6	8.0	11.2	13.8		
Radiation	28.9	26.4	20.8	15.6	11.7	9.3	9.9	12.6	16.8	23.2	27.5	30.1		
Evaporation	310	254	220	141	92	64	75	89	124	186	232	291	631	2078
Katanning PO														
Rainfall	13	17	22	31	61	79	76	63	46	37	21	16	362	482
Maximum Temp	30.3	29.4	26.7	22.6	18.3	15.4	14.4	15.4	17.7	20.6	25.0	28.4		
Minimum Temp	13.6	13.7	12.5	10.2	7.9	6.5	5.4	5.5	6.4	7.6	10.0	12.1		
Radiation	27.0	24.3	19.8	14.8	10.6	8.8	9.2	11.9	16.0	20.9	25.3	27.6		
Evaporation	259	213	182	111	72	51	59	68	91	138	181	238	478	1662
Kellerberrin														
Rainfall	10	15	22	22	43	58	53	41	26	19	12	13	240	334
Maximum Temp	33.9	33.3	30.2	25.5	20.6	17.4	16.3	17.5	20.7	24.5	28.8	32.0		
Minimum Temp	16.9	16.9	15.2	11.7	8.4	6.9	5.7	5.6	6.6	8.9	12.4	15.1		
Radiation	28.7	25.9	21.5	16.5	11.8	9.8	10.4	13.1	17.7	23.0	27.6	29.3		
Evaporation	319	266	233	147	96	65	75	91	126	190	238	297	643	2143
Kojonup PO														
Rainfall	13	16	22	32	68	91	88	75	53	42	23	15	417	538
Maximum Temp	29.3	28.5	26.1	21.8	17.9	15.1	14.3	14.7	16.8	20.0	23.4	27.6		
Minimum Temp	13.3	13.8	12.7	10.4	8.4	6.8	5.9	5.9	6.2	7.7	9.8	12.0		
Radiation	27.0	24.3	19.5	14.1	10.7	8.6	9.4	12.2	16.1	21.2	25.3	27.6		
Evaporation	250	207	176	105	68	48	55	64	85	128	171	228	48	1586
Kondinin														
Rainfall	10	17	20	23	45	57	53	43	28	21	17	12	247	346
Maximum Temp	33.2	32.5	28.8	23.6	20.1	16.8	15.8	16.4	19.3	23.5	27.4	32.1		
Minimum Temp	11.5	10.4	9.0	5.0	3.4	1.0	1.2	-0.9	-0.1	4.5	8.3	11.5		
Radiation	29.5	26.9	21.6	15.8	12.0	9.2	9.9	12.4	16.6	23.1	27.7	30.3		
Evaporation	302	248	216	136	89	61	71	85	117	177	223	282	601	2007
Lake Grace PO														
Rainfall	14	19	22	23	45	54	49	41	31	23	17	15	243	353
Maximum Temp	31.7	30.8	28.0	23.6	19.5	16.4	15.3	16.4	19.1	22.8	26.3	30.0		
Minimum Temp	14.8	15.1	13.8	11.3	8.3	6.8	5.6	5.5	6.6	8.5	11.2	13.4		
Radiation	29.3	26.0	21.2	15.5	11.7	9.1	9.9	12.7	17.0	22.7	26.7	29.6		
Evaporation	287	234	202	127	83	58	68	80	110	165	209	267	563	1889

APPENDIX I

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	M-O	Total
Merredin Shire														
Rainfall	11	13	21	23	41	54	53	38	26	19	13	11	231	322
Maximum Temp	33.2	32.6	29.5	24.5	20.2	17.0	16.0	16.6	19.5	24.1	28.6	31.9		
Minimum Temp	17.6	17.4	15.3	11.7	8.5	6.8	5.2	4.7	5.9	9.4	13.0	15.7		
Radiation	29.1	26.5	22.1	16.3	12.2	9.6	10.0	13.0	17.5	22.8	27.4	29.8		
Evaporation	329	272	239	153	100	69	79	96	134	201	249	308	678	2228
Mingenew PO														
Rainfall	7	13	17	23	56	90	81	59	32	20	10	6	338	414
Maximum Temp	36.2	36.3	34.1	27.6	23.8	20.1	19.1	19.7	22.6	26.8	30.5	34.7		
Minimum Temp	18.8	19.5	17.8	13.9	10.6	8.9	7.2	6.9	7.7	10.5	13.0	16.7		
Radiation	28.1	25.6	22.7	16.6	13.1	10.4	11.3	13.9	17.5	23.1	27.0	30.1		
Evaporation	343	297	268	170	113	75	81	104	142	210	259	314	725	2377
Moora														
Rainfall	10	15	19	24	61	94	90	64	38	25	12	9	372	461
Maximum Temp	33.9	33.8	30.5	25.5	21.5	18.5	17.0	17.7	20.1	24.2	27.9	31.3		
Minimum Temp	17.6	18.2	16.1	13.0	9.4	7.9	6.3	6.6	7.4	9.5	12.6	14.9		
Radiation	29.3	27.2	22.4	16.5	12.5	10.3	11.0	13.4	17.2	21.8	26.3	30.2		
Evaporation	320	275	243	150	98	65	71	89	123	185	235	292	630	2146
Morawa PO														
Rainfall	14	17	23	23	44	62	55	39	21	15	11	8	236	332
Maximum Temp	36.6	36.1	32.9	28.0	22.6	19.1	17.9	19.3	23.0	26.4	30.7	34.3		
Minimum Temp	18.8	19.4	17.3	13.5	9.5	7.3	6.0	6.3	7.6	10.1	13.6	16.4		
Radiation	29.6	27.6	24.0	18.0	13.9	10.7	12.0	14.7	19.1	25.2	28.6	30.2		
Evaporation	352	302	272	175	116	78	85	108	150	220	270	325	758	2453
Mt Barker PO														
Rainfall	23	24	36	56	85	98	107	93	82	73	42	30	538	749
Maximum Temp	26.2	25.9	24.0	21.0	17.6	15.2	14.2	15.0	16.8	18.7	21.8	24.3		
Minimum Temp	12.6	12.8	12.1	10.4	8.4	6.9	5.8	5.9	6.8	7.9	9.7	11.3		
Radiation	24.8	22.7	18.4	13.6	9.8	8.1	8.7	11.4	15.4	19.7	23.6	25.1		
Evaporation	233	190	160	97	64	46	54	61	80	119	159	215	424	1477
Mullewa														
Rainfall	13	16	20	20	46	68	61	43	21	14	8	7	253	337
Maximum Temp	36.5	36.2	33.6	28.3	23.2	19.6	18.4	19.8	23.3	26.7	30.8	34.2		
Minimum Temp	19.6	20.1	18.3	14.8	11.0	8.6	6.9	7.1	8.6	11.1	14.4	17.1		
Radiation	29.6	27.7	24.2	18.6	14.3	11.3	11.9	15.0	20.0	25.7	29.1	30.2		
Evaporation	356	308	280	182	122	82	89	113	156	226	275	329	788	2518
Muresk														
Rainfall	10	15	20	27	63	91	90	63	35	26	12	9	368	461
Maximum Temp	34.1	33.3	30.4	25.3	20.6	17.4	16.3	17.3	19.8	23.6	28.1	31.9		
Minimum Temp	16.2	16.1	14.6	10.8	7.4	6.1	5.0	4.8	5.7	7.6	11.0	14.2		
Radiation	29.1	26.2	21.7	16.2	11.3	9.3	9.8	12.2	15.7	21.3	27.0	29.4		
Evaporation	302	255	223	137	88	59	66	81	112	170	218	276	576	1988
Narembeen PO														
Rainfall	11	19	20	23	42	55	50	41	25	19	16	12	232	333
Maximum Temp	33.6	32.7	30.0	25.2	20.5	17.3	16.5	17.3	20.4	24.6	27.7	31.7		
Minimum Temp	16.4	16.4	14.5	11.7	7.9	6.3	5.4	5.2	6.0	9.0	12.0	14.5		
Radiation	29.6	26.6	22.2	15.8	11.7	9.5	10.5	13.1	17.3	22.9	27.5	30.4		
Evaporation	315	259	226	144	94	65	75	90	125	189	235	294	638	2111

APPENDIX I

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	M-O	Total
Narrogin														
Rainfall	10	17	21	30	65	92	89	69	47	34	18	13	396	505
Maximum Temp	30.8	30.0	27.2	22.4	18.2	15.3	14.6	15.1	17.3	21.2	24.9	28.9		
Minimum Temp	14.7	14.9	13.6	10.9	8.1	7.0	5.8	5.6	6.2	8.1	10.7	12.9		
Radiation	27.4	24.8	19.8	14.4	10.6	8.5	9.8	12.0	15.8	21.0	25.0	26.9		
Evaporation	276	230	198	120	78	53	61	72	98	149	195	253	513	1785
Ongerup PO														
Rainfall	17	19	21	26	44	52	50	42	38	34	24	14	260	381
Maximum Temp	29.0	28.0	25.8	22.3	18.5	15.8	14.9	15.5	17.7	21.1	24.1	27.6		
Minimum Temp	13.8	14.3	12.9	10.8	8.3	6.6	5.8	5.7	6.3	8.0	10.5	12.4		
Radiation	27.6	24.5	20.0	14.6	10.7	8.8	9.6	12.1	16.0	22.0	26.7	28.6		
Evaporation	262	212	181	113	74	53	63	72	97	145	186	244	504	1702
Pingelly														
Rainfall	9	14	17	28	61	87	84	63	41	26	15	11	362	456
Maximum Temp	31.7	31.2	28.2	23.5	19.2	16.0	15.2	15.7	18.1	21.7	25.5	29.9		
Minimum Temp	15.6	16.2	14.6	11.6	8.6	6.6	5.8	5.6	6.3	8.1	11.2	13.9		
Radiation	29.3	27.3	22.6	15.5	11.6	8.9	9.1	12.2	16.2	21.3	25.5	28.4		
Evaporation	286	239	208	127	82	56	63	76	104	158	205	262	538	1865
Ravensthorpe														
Rainfall	20	23	32	34	42	45	46	43	41	38	27	20	255	413
Maximum Temp	29.1	28.2	26.3	23.2	19.7	17.2	16.2	17.0	19.0	22.4	25.0	27.6		
Minimum Temp	13.9	14.1	13.1	11.5	9.3	7.9	6.6	6.3	7.0	8.9	10.8	12.7		
Radiation	27.5	24.6	20.5	15.3	11.6	9.5	10.4	13.1	17.4	23.2	26.6	27.9		
Evaporation	288	231	198	128	85	61	72	84	116	173	214	272	591	1924
Salmon Gums Res. Stn.														
Rainfall	21	23	22	25	34	41	37	33	31	28	26	19	204	340
Maximum Temp	30.4	29.6	27.4	23.3	19.3	16.7	16.0	17.2	20.3	23.1	26.0	29.0		
Minimum Temp	13.8	14.1	12.6	9.8	6.9	5.5	4.5	4.6	5.8	7.5	10.1	12.3		
Radiation	27.6	24.6	20.1	15.2	11.5	9.7	10.4	13.0	17.3	22.4	26.7	28.5		
Evaporation	318	255	220	146	97	69	81	97	136	202	243	301	683	2165
Wagin PO														
Rainfall	11	16	19	30	56	76	73	58	42	30	17	12	335	440
Maximum Temp	31.1	29.6	27.6	23.3	19.2	16.0	15.2	15.7	18.0	21.4	24.9	29.3		
Minimum Temp	14.4	14.8	13.1	10.3	7.7	6.2	5.7	5.4	5.8	7.4	10.5	12.9		
Radiation	27.9	25.3	19.7	15.4	11.3	8.7	9.8	12.6	16.7	21.6	26.4	30.0		
Evaporation	268	222	190	116	75	52	60	70	95	143	188	246	495	1724
Wandering PO														
Rainfall	10	15	20	35	79	118	115	94	61	43	19	14	510	623
Maximum Temp	31.7	31.0	28.2	23.5	18.9	16.0	15.1	16.0	18.1	21.3	25.8	29.5		
Minimum Temp	13.7	13.7	12.0	8.9	6.3	5.0	4.1	4.0	4.8	6.2	9.1	11.9		
Radiation	28.6	25.7	20.9	14.9	10.9	8.8	9.6	11.9	15.4	20.8	26.1	29.0		
Evaporation	276	233	202	121	78	53	59	71	97	147	194	252	505	1783
Watheroo (8130)														
Rainfall	14	18	23	23	55	86	79	59	35	22	9	8	336	432
Maximum Temp	33.7	33.7	30.9	26.6	21.4	18.0	17.1	18.3	21.0	23.8	28.5	31.9		
Minimum Temp	15.6	15.8	14.5	11.1	8.0	5.9	4.9	5.4	6.4	8.1	11.5	1		
Radiation	29.0	26.9	22.8	17.8	12.8	10.4	10.8	13.8	18.5	23.3	28.2	29.6		
Evaporation	330	282	251	157	103	68	75	94	130	195	245	302	665	2233

APPENDIX I

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	M-O	Total
Narrogin														
Rainfall	10	17	21	30	65	92	89	69	47	34	18	13	396	505
Maximum Temp	30.8	30.0	27.2	22.4	18.2	15.3	14.6	15.1	17.3	21.2	24.9	28.9		
Minimum Temp	14.7	14.9	13.6	10.9	8.1	7.0	5.8	5.6	6.2	8.1	10.7	12.9		
Radiation	27.4	24.8	19.8	14.4	10.6	8.5	9.8	12.0	15.8	21.0	25.0	26.9		
Evaporation	276	230	198	120	78	53	61	72	98	149	195	253	513	1785
Ongerup PO														
Rainfall	17	19	21	26	44	52	50	42	38	34	24	14	260	381
Maximum Temp	29.0	28.0	25.8	22.3	18.5	15.8	14.9	15.5	17.7	21.1	24.1	27.6		
Minimum Temp	13.8	14.3	12.9	10.8	8.3	6.6	5.8	5.7	6.3	8.0	10.5	12.4		
Radiation	27.6	24.5	20.0	14.6	10.7	8.8	9.6	12.1	16.0	22.0	26.7	28.6		
Evaporation	262	212	181	113	74	53	63	72	97	145	186	244	504	1702
Pingelly														
Rainfall	9	14	17	28	61	87	84	63	41	26	15	11	362	456
Maximum Temp	31.7	31.2	28.2	23.5	19.2	16.0	15.2	15.7	18.1	21.7	25.5	29.9		
Minimum Temp	15.6	16.2	14.6	11.6	8.6	6.6	5.8	5.6	6.3	8.1	11.2	13.9		
Radiation	29.3	27.3	22.6	15.5	11.6	8.9	9.1	12.2	16.2	21.3	25.5	28.4		
Evaporation	286	239	208	127	82	56	63	76	104	158	205	262	538	1865
Ravensthorpe														
Rainfall	20	23	32	34	42	45	46	43	41	38	27	20	255	413
Maximum Temp	29.1	28.2	26.3	23.2	19.7	17.2	16.2	17.0	19.0	22.4	25.0	27.6		
Minimum Temp	13.9	14.1	13.1	11.5	9.3	7.9	6.6	6.3	7.0	8.9	10.8	12.7		
Radiation	27.5	24.6	20.5	15.3	11.6	9.5	10.4	13.1	17.4	23.2	26.6	27.9		
Evaporation	288	231	198	128	85	61	72	84	116	173	214	272	591	1924
Salmon Gums Res. Stn.														
Rainfall	21	23	22	25	34	41	37	33	31	28	26	19	204	340
Maximum Temp	30.4	29.6	27.4	23.3	19.3	16.7	16.0	17.2	20.3	23.1	26.0	29.0		
Minimum Temp	13.8	14.1	12.6	9.8	6.9	5.5	4.5	4.6	5.8	7.5	10.1	12.3		
Radiation	27.6	24.6	20.1	15.2	11.5	9.7	10.4	13.0	17.3	22.4	26.7	28.5		
Evaporation	318	255	220	146	97	69	81	97	136	202	243	301	683	2165
Wagin PO														
Rainfall	11	16	19	30	56	76	73	58	42	30	17	12	335	440
Maximum Temp	31.1	29.6	27.6	23.3	19.2	16.0	15.2	15.7	18.0	21.4	24.9	29.3		
Minimum Temp	14.4	14.8	13.1	10.3	7.7	6.2	5.7	5.4	5.8	7.4	10.5	12.9		
Radiation	27.9	25.3	19.7	15.4	11.3	8.7	9.8	12.6	16.7	21.6	26.4	30.0		
Evaporation	268	222	190	116	75	52	60	70	95	143	188	246	495	1724
Wandering PO														
Rainfall	10	15	20	35	79	118	115	94	61	43	19	14	510	623
Maximum Temp	31.7	31.0	28.2	23.5	18.9	16.0	15.1	16.0	18.1	21.3	25.8	29.5		
Minimum Temp	13.7	13.7	12.0	8.9	6.3	5.0	4.1	4.0	4.8	6.2	9.1	11.9		
Radiation	28.6	25.7	20.9	14.9	10.9	8.8	9.6	11.9	15.4	20.8	26.1	29.0		
Evaporation	276	233	202	121	78	53	59	71	97	147	194	252	505	1783
Watheroo (8130)														
Rainfall	14	18	23	23	55	86	79	59	35	22	9	8	336	432
Maximum Temp	33.7	33.7	30.9	26.6	21.4	18.0	17.1	18.3	21.0	23.8	28.5	31.9		
Minimum Temp	15.6	15.8	14.5	11.1	8.0	5.9	4.9	5.4	6.4	8.1	11.5	1		
Radiation	29.0	26.9	22.8	17.8	12.8	10.4	10.8	13.8	18.5	23.3	28.2	29.6		
Evaporation	330	282	251	157	103	68	75	94	130	195	245	302	665	2233

APPENDIX II

Main soil groups occurring in the wheat growing areas of Western Australian

Super group	Soil Group name	Description	Common soil properties	Australian Soil Classification (Isbell, 1996)	Distribution within the South-west	Land use considerations for wheat
Rocky or stony soils More than 50% coarse fragments (>20 mm) throughout the profile.	**Bare rock**	*Rock outcrop*	Bare rock exposed on surface Minimal soil development Excludes duricrust outcrop	Not applicable or Rudosol	Covers approximately 2% of the Wheatbelt. Occurs throughout the area, most common in hilly terrain or deeply incised valleys	Unsuitable for wheat growth. Shedding of water may contribute to water erosion of surrounding soils.
	Stony soil	*Stony throughout*	Rocks or stones dominant throughout the profile Usually shallow with sandy, loamy, clayey or gravelly matrix	Rudosols Tenosols	Covers approximately 1% of the Wheatbelt. Occurs throughout the area, most common in hilly terrain or deeply incised valleys.	Water-holding capacity low due to shallow depth and high stone content. Stone present obstacle to cultivation.
Ironstone gravelly soils Ironstone gravel (>20% and >20 cm thick), or duricrust, within the top 15 cm. Ironstone gravels a dominant feature of the profile.	**Shallow gravel**	*Ironstone gravel soil less than 80 cm deep over cemented gravels (duricrust)*	Yellow/brown to grey (sometimes red) colour Neutral to acid pH High gravel conten Sandy or loamy matrix	Kandosols Tenosols	Covers approximately 4% of the Wheatbelt. Widespread on lateritic plateau remnants.	Generally has insufficient depth for cropping.
	Duplex sandy gravel	*Sandy ironstone gravel soil 30-80 cm deep over clay or reticulite*	Yellow, brown or grey colour topsoil Neutral to acid pH High gravel content in topsoil Over clay or reticulite at 30 to 80 cm	Kandosols Tenosols Chromosols	Covers approximately 3% of the Wheatbelt. Found on lateritic plateau remnants, especially in the West Midlands and between Moora and Kataning. Also associated with sandplains in the northern and central Wheatbelt and along the South Coast.	Usually productive though high gravel content in the topsoil may reduce water availability Clayey subsoil can form a barrier to water movement and result in the development of perched water tables.
	Deep sandy gravel	*Sandy ironstone gravel soil greater than 80 cm deep over clay or cemented gravels*	Yellow, brown or grey colour Neutral to acid pH High gravel content in throughout Usually over lies clayey subsoil or cemented gravels at more than 80 cm	Kandosols Tenosols Chromosols	Covers approximately 1% of the Wheatbelt. Found on lateritic plateau remnants, especially in the West Midlands and between Moora and Kataning. Also associated with sandplains from Corrigin southwards and along the South Coast.	Usually productive though high gravel content can reduce water availability

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Super group	Soil Group name	Description	Common soil properties	Australian Soil Classification (Isbell, 1996)	Distribution within the South-west	Land use considerations for wheat
Ironstone gravelly soils (continued)	**Loamy gravel**	*Loamy ironstone gravel soil, often grading to clay at more than 30 cm*	Yellow, red or brown colour Neutral to acid pH High gravel content in topsoil Usually grading to clay by 30-80 cm but occasionally deeper	Kandosols Tenosols Chromosols Dermosols	Covers approximately 1% of the Wheatbelt. Found on lateritic plateau remnants, especially in the West Midlands and between Moora and Kataning. Also associated with sandplains in the northern and central Wheatbelt.	Usually productive
Shallow sands Sands less than 80 cm deep over rock, hardpan or other cemented layer.	**Yellow/brown shallow sand**	*Yellow or brown sand over rock, hardpan or other cemented layer at less than 80 cm*	White, grey or pale yellow topsoil Neutral to acid pH Sometimes occurs over limestone in coastal areas	Rudosols Tensosols	Covers approximately 1% of the Wheatbelt. Found on lateritic plateau remnants, especially in the West Midlands. Also associated with sandplains from Corrigin southwards	Poor water-holdingcapacity Often insufficient rooting depth
Deep sands Sands (sands, loamy sands and clayey sands) more than 80 cm deep.	**Pale deep sand**	*White, grey or pale yellow sand more than 80 cm deep*	White, grey or pale yellow coloured topsoil Neutral to acid pH Ironstone gravel may be present in small quantities Weak coffee rock layer may be present	Rudosols Tenosols Podosols	Covers approximately 7% of the Wheatbelt. Most commonly associated with sandplains in the West Midlands and along the South Coast.	Poor nutrient and water retention characteristics Prone to wind erosion and non-wetting problems. High recharge risk
	Yellow deep sand	*Yellow sands greater than 80 cm deep*	Yellow or yellow-brown topsoil Neutral to acid pH Ironstone gravel may be present below 15 cm Ironstone duricrust or limestone may be present below 80 cm	Tenosols	Covers approximately 5% of the Wheatbelt. Most commonly associated with sandplains in the West Midlands and inland of a line between Geraldton and Corrigin.	Moderate nutrient and water retention characteristics. Susceptible to wind erosion. Moderate recharge risk.
	Gravelly pale deep sand	*Pale sand over gravelly sand at 15-80 cm*	White, grey or pale yellow colour Ironstone gravel layer (>20% gravel and at least 20 cm thick) commences at 15-80 cm. Neutral to acid pH Coffee rock, clay or duricrust may be present at more than 80 cm	Rudosols Tenosols	Covers approximately 1% of the Wheatbelt. Most commonly associated with sandplains in the West Midlands.	Poor nutrient and water retention characteristics. Prone to wind erosion and non-wetting problems. High recharge risk.

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Super group	Soil Group name	Description	Common soil properties	Australian Soil Classification (Isbell, 1996)	Distribution within the South-west	Land use considerations for wheat
Deep sands (continued)	**Brown deep sand**	*Brown sand more than 80 cm deep*	Brown within 30 cm (sometimes has a black surface) Sandy throughout Neutral to acid pH Often occurs in alluvial deposits	Tenosols Podosols	Covers approximately 1% of the Wheatbelt. Mostly limited to river flats.	Usually productive.
Sandy earths Soils with a sandy surface and grading to loam by 80 cm. May grade to clay at depth.	**Brown sandy earth**	*Brown sand grading to loam by 80 cm*	Brown topsoil Neutral to acid pH Usually alluvial May grade to clay at depth	Kandosols	Covers approximately 1% of the Wheatbelt. Mostly limited to river flats.	Highly productive.
	Acid yellow sandy earth	*Strongly acid yellow sand grading to loam by 80 cm*	Yellow throughout (may have grey surface) Strongly acid pH (especially subsoil) Ironstone gravel may be present in subsoil	Kandosols Tensosols	Covers approximately 1% of the Wheatbelt, mostly on sandplains between Merredin and Morowa.	Low pH and high aluminum concentration severely limit root growth and yields.
	Yellow sandy earth	*Yellow sand grading to loam by 80 cm*	Yellow topsoil Neutral to acid pH Ironstone gravel may be present in subsoil Usually porous and massive or poorly structured May grade to clay at depth	Kandosols	Covers approximately 5% of the Wheatbelt. Most commonly associated with sandplains in the West Midlands and inland of a line between Geraldton and Corrigin.	Highly productive. May be prone to subsoil acidification.
Sandy duplexes Soils with a sandy surface and a texture or permeability contrast at 3-80 cm.	**Alkaline grey shallow sandy duplex**	*Grey sand less than 30 cm deep over alkaline clay*	Grey surface, bleached sub-surface Various colours in subsoil, mottling is common Subsoil has alkaline pH (often calcareous) Usually sodic May include sandy loams Usually not hardsetting	Sodosols	Covers approximately 9% of the Wheatbelt. Common on slopes and valley floors on truncated laterite to the south of Katanning, Lake Grace and the South Cosat.	Waterlogging often occurs in topsoil due to sodic subsoil. Conditions in sodic subsoil may restrict root growth. Surface sealing may occur under cultivation

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Super group	Soil Group name	Description	Common soil properties	Australian Soil Classification (Isbell, 1996)	Distribution within the South-west	Land use considerations for wheat
Sandy duplexes (continued)	**Alkaline grey shallow deep duplex**	*Grey sand 30-80 cm deep over alkaline clay*	Grey surface Various colours in subsoil Subsoil has alkaline pH (often calcareous) Subsoil often sodic	Chromosols Sodosols	Covers approximately 3% of the Wheatbelt. Common on slopes and valley floors on truncated laterite between Moora and the South Coast.	Waterlogging often occurs in topsoil due to sodic subsoil. Conditions in sodic subsoil may restrict root growth. Sandy topsoil may be prone to wind erosion.
	Grey deep sandy duplex	*Grey sand 30-80 cm deep over non-alkaline clay*	Grey, bleached sub-surface Various colours in subsoil, mottling is common Neutral to acid pH Non-sodic and sodic subsoils Ironstone gravel layer often present above the clay	Chromosols Sodosols	Covers approximately 10% of the Wheatbelt. Widespread and common on slopes and valley floors on truncated laterite between Moora and the South Coast, also assocaited with sandplains in the west Midlands.	Sandy topsoil may become seasonally waterlogged. Conditions in sodic subsoils may restrict root growth. Sandy topsoil may be prone to wind erosion.
	Grey shallow sandy duplex	*Grey sand less than 30 cm deep over non-alkaline clay*	Grey, bleached sub-surface Various colours in subsoil, mottling is common Neutral to acid pH Non-sodic and sodic subsoils Ironstone gravel layer often present above the clay	Chromosols Sodosols	Covers approximately 6% of the Wheatbelt. Widespread and common on slopes and valley floors on truncated laterite between Moora and the South Coast, also assocaited with sandplains in the west Midlands.	Sandy topsoil may become seasonally waterlogged. Conditions in sodic subsoils may restrict root growth. Sandy topsoil may be prone to wind erosion.
	Reticulite deep sandy duplex	*Grey to yellow or brown sand 30-80 cm deep over reticulite (mottled loamy sand to sandy clay loam)*	Grey to yellow or brown topsoil Neutral to acid pH Reticulite present at 30-80 cm Ironstone gravel layer often present above the clay	Tenosols Kandosols Chromosols	Covers approximately 1% of the Wheatbelt. Southern and central parts of the Wheatbelt and upper Great Southern	Sandy topsoil may be prone to wind erosion.
Loamy earths Soils with a loamy surface (sandy loam to clay loam) and either loamy throughout or grading to clay by 80 cm.	**Calcareous loamy earth**	*Calcareous loam (may grade to calcareous clay at depth)*	Usually calcareous throughout (sometime topsoil is non-calcareous) Usually red or brown topsoil (may be grey) Either loam throughout or grading to clay with depth May have limestone or calcrete at depth Hardsetting or fluffy surface Sometimes salty	Calcarosols Dermosols	Covers approximately 5% of the Wheatbelt. Common on valley floors in the to the north and south of Merredin and in the mallee country north of Esperance.	High lime content may inhibit root growth. Subsalinity levels can be high. Sometimes non-wetting.

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Super group	Soil Group name	Description	Common soil properties	Australian Soil Classification (Isbell, 1996)	Distribution within the South-west	Land use considerations for wheat
	Red loamy earth	*Red loam (may grade to clay at depth)*	Red topsoil Neutral to acid pH, sometimes calcareous and alkaline at depth Hardsetting or crusting surface Usually massive or poorly structured Ironstone gravel may be present	Kandosols	Covers approximately 2% of the Wheatbelt. Most common to the north and east of Geraldton, but scattered throughout the agricultural area	Can be highly productive. Hardsetting topsoil can be a problem.
Loamy duplexes Soils with a loamy surface and a texture or permeability contrast at 3-80 cm.	**Acid shallow duplex**	*Loam or sand less than 30 cm deep over strongly acid clay*	Shallow loam or occasionally loamy sand topsoil Pink, grey or brown clay subsoil Strongly acid pH in subsoil Subsoil often sodic	Kurosols	Covers approximately 1% of the Wheatbelt. Found below breakaways between Morowa and Jerramungup.	Poor crop performance. Acidity (and often sodicity and salinity) adversely affect root growth. Non-wetting and surface sealing problems are common. Prone to water erosion.
	Alkaline grey shallow loamy duplex	*Grey loam less than 30 cm deep over alkaline clay*	Grey, sometimes brown topsoil Subsoil has alkaline pH (often calcareous) Surface commonly hardsetting Subsoil often sodic	Sodosols Chromosols	Covers approximately 2% of the Wheatbelt. Common on slopes and valley floors on truncated ,especially between Katanning, Lake Grace and Ravensthorpe and to the north of Esperance.	Waterlogging often occurs in topsoil due to sodic subsoil. Conditions in sodic subsoil may restrict root growth. Surface sealing may occur under cultivation.
	Alkaline red shallow loamy duplex	*Red loam less than 30 cm deep over alkaline clay*	Red topsoil Subsoil has alkaline pH (usually calcareous) Surface commonly hardsetting Subsoil sometimes sodic Grey, sometimes brown Calcareous subsoil (alkaline pH)∑ Hardsetting surface	Chromosols Sodosols Kandosols	Covers approximately 2% of the Wheatbelt. Most common between Morowa and Corrigin.	Surface prone to hardsetting.
	Grey shallow loamy duplex	*Grey to brown loam less than 30 cm deep over non-alkaline clay*	Grey or brown topsoil Neutral subsoil pH (non-calcareous) Firm to hardsetting surface	Chromosols Kandosols	Covers approximately 1% of the Wheatbelt. Most common on truncated laterite between Katanning, Lake Grace and Ravensthorpe.	Seasonal waterlogging may occur above clayey subsoil. Surface sealing may occur under cultivation.

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Super group	Soil Group name	Description	Common soil properties	Australian Soil Classification (Isbell, 1996)	Distribution within the South-west	Land use considerations for wheat
Loamy duplexes (continued)	**Yellow/brown shallow loamy duplex**	*Yellow/brown loam less than 30 cm deep over clay*	Yellow or brown topsoil Usually neutral subsoil pH Firm to hardsetting surface	Sodosols Chromosols	Covers approximately 1% of the Wheatbelt. Minor soil scattered throughout agricultural region, mainly on alluvial deposits or fresh rock.	Productive soil. Seasonal waterlogging may occur above clayey subsoil.
	Red shallow loamy duplex	*Red loam less than 30 cm deep over non-alkaline clay*	Red or red-brown topsoil Neutral to alkaline subsoil pH Firm to hardsetting surface	Chromosols Kandosols	Covers approximately 1% of the Wheatbelt.	Productive soil. Seasonal waterlogging may occur above clayey subsoil. Often prone to water erosion.
	Red deep loamy duplex	*Red to brown loam 30-80 cm deep clay*	Red or red-brown topsoil Neutral to alkaline subsoil pH Subsoil may be calcareous Firm to hardsetting surface	Chromosols Sodosls Kandosols	Covers approximately 1% of the Wheatbelt. Most commonly associated with fresh rock between Narrogin and Moora.	Productive soil. Seasonal waterlogging may occur above clayey subsoil.
Shallow loams Loams less than 80 cm deep over rock, hardpan or other cemented layer.	Red shallow loam	*Red loam less than 80 cm deep over rock or hardpan*	Red coloured loam Rock, hardpan or other cemented layer by 80 cm (typically by 30 cm) Usually nuetral to acid pH	Kandosol	Covers approximately 1% of the Wheatbelt. Most common to between Merredina and Morowa.	Shallow depth limits rooting depth and water-holding capacity.
	Red-brown hardpan shallow loam	*Red loam less than 50 cm deep over red-brown hardpan*	Red coloured loam Red-brown hardpan by 50 cm Usually nuetral to acid pH	Kandosol	Covers approximately 2% of the Wheatbelt. Most common to the north of Geraldton and Morowa.	Shallow depth limits rooting depth and water-holding capacity.
Cracking clays Soils that have a clayey surface (light to heavy clay or sandy clay) at least 30 cm thick and crack strongly when dry.	Hard cracking clay	*Cracking clay without a self-mulching surface*	Red, brown, yellow or grey topsoil Clay texture throughout Deep cracks when dry Variable pH Massive or pedal May have a crusting surface	Vertosols	Covers approximately 1% of the Wheatbelt. Locally common on valley floors between Jerramungup and Morowa .	Plant water availability may be low in dry seasons due to high water retention by heavy clays.
Non-cracking clays Soils that have a clayey surface (light to heavy clay or sandy clay) at least 30 cm thick and do not crack strongly when dry.	Red/brown non-cracking clay	*Red or brown non-cracking clay, usually with good structure*	Red or brown topsoil Clay texture throughout Subsoil sometimes calcareous Does not seasonally crack Usually structured and friable Often has hardsetting surface	Dermosols Kandosols Ferrosols	Covers approximately 1% of the Wheatbelt. Widespread but rarely common, usually associated with dolerite dykes.	Subject to soil structure decline.

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Super group	Soil Group name	Description	Common soil properties	Australian Soil Classification (Isbell, 1996)	Distribution within the South-west	Land use considerations for wheat
	Grey non-cracking clay	*Grey non-cracking clay*	Often grey topsoil, sometimes yellow or brown Clay texture throughout Subsoil often calcareous Does not seasonally crack Often has hardsetting surface	Kandosols Dermosols	Covers approximately 1% of the Wheatbelt. Localy common between Katanning, Lake Grace and Ravensthorpe.	Plant water availability may be low in dry seasons due to high water retention by heavy clays. Can be boggy and difficult to cultivate when wet.
Wet or water-logged soils Soils seasonally wet	*Salt lake soil*	Variable, seasonally wet, salt lake soil	Soils affected by high to extreme salinity Seasonally wet to within 80 cm of the surface for a major part of the year Includes sands, loams and clays Often gypsiferous Often calcareous	Hydrosols	Covers approximately 3% of the Wheatbelt. Mainly on valley floors between Jerramungup and Morowa.	Waterlogging and high salinity severely limit growth.
to within 80 cm of the surface for a major part of the year.	Saline wet soil	*Seasonally wet soil subject to secondary salinity*	Soils affected by moderate to extreme secondary salinity Seasonally wet to within 80 cm of the surface for a major part of the year Includes sands, loams and clays	Hydrosols	Covers approximately 3% of the Wheatbelt. Common on valley floors in the Wheatbelt and Woolbelt.	Waterlogging and high salinity severely limit growth.
	Semi-wet soil	*Non-saline soils waterlogged at 30-80 cm for a major part of the year. Does not include soils with a temporary perched watertable.*	Lower part of the profile saturated for a major part of the year Includes sands, loams and clays Acid to neutral pH Variable subsoil, may contain bog-iron	Hydrosols, Chromosols, Kandosols, Podosols, Rudosols, Tenosols and Sodosols	Covers approximately 1% of the Wheatbelt. Most common on the South Coast and hinterland.	Waterlogging moderately limits growth, artificial drainge may be an option.

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Photo: Simon Eyres. Wheat crop near Wongan Hills