Factors affecting frost damage to wheat in Western Australia

S P. Loss

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FACTORS AFFECTING FROST DAMAGE TO WHEAT IN WESTERN AUSTRALIA

by S.P. Loss

TECHNICAL REPORT №6
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FACTORS AFFECTING FROST DAMAGE TO WHEAT

IN WESTERN AUSTRALIA

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INTRODUCTION

It may at first seem strange that precious research funds are being channelled into a project concerned with frost damage in a country where high temperatures and moisture stress limit the growth of plants for a large portion of the year. But cereal crops are only grown in the temperate zones of the continent during winter and spring when they may be exposed to low diurnal temperatures. In many areas cold damage is irregular and rare, however it limits yields not only by causing actual damage but also by restricting the most effective period for flowering. For much of the Australian wheat crop excessive risk of frost damage sets the earliest date for flowering and the beginning of grain filling at a time when other conditions are at their most favourable for carbohydrate assimilation. The latest date for flowering is determined by high temperatures and low water availability towards the end of the grain filling phase. An optimum flowering time and maximised yield in the long term are achieved when a compromise between the effects of frost and drought is reached.

Frosts were estimated to have cost cereal farmers in Western Australia's Great Southern $1.25 million in 1980 (T. Negus, personal communication), $4.78 million in 1981 (P. Fievez, personal communication) and $1.5 million in 1985 (S. Loss, unpublished data). Losses due to frost were also evident in 1982 and in 1984. These losses amount to an average of greater than $1.25 million per year for the last 6 years. Farmers in this region of the Western Australian wheatbelt are beginning to consider sheep production and oats (a less susceptible crop) "safer" and more profitable in the long term than cropping wheat. Those farmers who persist with wheat and barley do not take advantage of early breaks to the season because of a fear of frost damage near flowering. How justified is this fear of frost and how can frost damage be minimized in Western Australia?

This technical bulletin describes the current understanding of how physical processes combine to cause the air temperatures near the ground to fall below 0°C and how wheat plants react to these sub-zero temperatures. This is applied to the physical and biotic conditions in Western Australia and frost avoidance strategies are discussed. Finally, the bulletin describes current areas of frost research and how increased knowledge in these areas will reduce the amount of frost damage in Western Australia.
1.0 PHYSICAL ASPECTS OF FROST DEVELOPMENT

It is important to understand what physical processes cause the air temperature near the ground to fall below 0°C.

1.1 Meteorological Aspects - The prevailing meteorological conditions affect the average minimum temperatures experienced near the ground over widespread regions. What conditions cause sub-zero temperatures near the ground?

1.1.1 Energy Balance of the Soil - The First Law of Thermodynamics states that energy cannot be created or destroyed but only transformed from one form to another. Hence, the long term sum of the energy absorbed and lost by the earth will be zero if the earth remains at the same temperature.

Energy from the sun, in the form of shortwave radiation passes through the earth's atmosphere and is received on the earth's surface as solar radiation or sunlight (S†). The solar radiation is partly reflected by the ground back toward the atmosphere (S†) and the remainder is absorbed and transformed into thermal energy. As the sun's shortwave radiation passes through the atmosphere, a portion of it is absorbed by dust, water vapour and other gases, and it is transformed into thermal energy. This energy is also radiated toward the earth's surface in the form of atmospheric thermal or longwave radiation (L†). The ground similarly possesses thermal energy which is partly radiated back toward the atmosphere in the form of terrestrial thermal radiation (L†). The radiation balance of the ground can thus basically be defined as:

\[ R_n = (S† + L†) - (S† + L†) \]

where

- \( R_n \) = net radiation
- \( S† \) = solar radiation
- \( L† \) = atmospheric thermal radiation
- \( L† \) = terrestrial thermal radiation
- \( S† \) = reflected solar radiation

An example of such a balance is given below

Table 1. The components of the annual radiation balance equation, measured at the Meteorological Observatory, Hamburg, Germany in 1954. (Fleischer and Grafe, 1955).

<table>
<thead>
<tr>
<th>Component</th>
<th>MJ/m²/Day*</th>
</tr>
</thead>
<tbody>
<tr>
<td>( S† )</td>
<td>+27.60</td>
</tr>
<tr>
<td>( L† )</td>
<td>+ 8.90</td>
</tr>
<tr>
<td>( S† )</td>
<td>- 1.65</td>
</tr>
<tr>
<td>( L† )</td>
<td>-30.84</td>
</tr>
<tr>
<td>( R_n )</td>
<td>4.01</td>
</tr>
</tbody>
</table>

* average values over the year.
If the mean soil temperature remained identical to the previous year's how was the 4.01 MJ/m²/day used in the soil? The energy balance of the soil surface is complicated by other energy exchange processes. Thermal energy may be conducted to or from the soil surface depending upon its temperature relative to the sub-soil and its thermal conductivity. Energy is also lost by evaporation from the soil surface. The convection of air near the soil surface can cause energy losses or gains. The long-term energy balance of the soil can be defined as:

\[
\text{energy gains} = \text{energy losses} \\
(S^+ + L^+) = (S^+ + L^+) + (E+C+G)
\]

where

- \( E \) = evaporative energy loss
- \( C \) = convection energy loss
- \( G \) = conduction energy loss

At Hamburg, 86% of the net radiation was used by evaporation and the remainder, in heating the air. The net conduction of energy from the soil surface was equal to zero over the whole year.

So far we have considered the energy balance of the soil on an annual time scale. Let us now consider the effects of specific meteorological conditions on the instantaneous energy balance of the soil during the day and at night and how these conditions affect the air temperatures near the ground.

1.1.2 During the Day – During the day the radiation balance of the ground is positive. The sum of the solar radiation and the atmospheric thermal radiation is greater than the sum of the reflected solar radiation and the terrestrial thermal radiation (See Table 2 below).

<table>
<thead>
<tr>
<th>Component</th>
<th>Radiation Fluxes*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(a)</td>
</tr>
<tr>
<td>( S^+ )</td>
<td>+1000</td>
</tr>
<tr>
<td>( L^+ )</td>
<td>+370</td>
</tr>
<tr>
<td>( S^- )</td>
<td>-200</td>
</tr>
<tr>
<td>( L^- )</td>
<td>-420</td>
</tr>
<tr>
<td>( R_n )</td>
<td>+750</td>
</tr>
</tbody>
</table>

* N.B. all fluxes in W/m²
This positive radiation energy balance during the day, causes the ground to become heated and some of this heat is conducted to the depths of the soil. See Fig. 1(a). The air near the ground surface is heated by conduction and rises because of its lower density. It mixes with cooler upper air layers, so that the temperature of the air falls rapidly for the first few metres above the ground and then more slowly with further increases in height. A temperature-height profile forms during the day as depicted in Fig. 2(a).

1.1.3 **During the Night** - During the night the ground receives no solar radiation and its radiation balance becomes negative. (See Table 2.) Losses of energy from the ground through convection, evaporation and reflected solar radiation are negligible or do not occur during the night but the thermal radiation emitted by the ground causes the ground to cool. This is called radiative cooling and hence the term "radiation frost". See Fig. 1(b). The air immediately above the ground is also cooled through contact with the cold ground surface and it remains near the ground because it is denser than the upper layers of warm air which rose during the day. This causes the temperature of the air above the ground to rise in the first few metres giving the reverse of the day-time profile. Above a particular height the air temperature slowly falls, giving a similar profile to that during the day. The night-time profile is termed an "inversion profile" and is also depicted in Fig. 2(a).

1.1.4 **Air Movement Effects** - Air movement or wind will have a dampening effect on the diurnal fluctuation of temperatures near the ground. At night, the mixing of warm air from the inversion layer with the cooler air near the ground results in a "weaker" or cooler inversion layer and warmer temperatures experienced near the ground. The reverse is the case during the day. See Fig. 2(b). Air movement also increases the heat exchange between the ground and the air, increasing convective heat losses by the ground during the day and increasing convective heat gains during the night. Hence, temperature extremes near the ground are usually experienced during still conditions.

1.1.5 **Air Moisture Effects** - Terrestrial thermal radiation lost by the ground is absorbed by dust particles and water vapour in the atmosphere and then radiated back to the ground in the form of atmospheric thermal radiation. During cloudy, humid or smoky conditions the amount of terrestrial thermal radiation absorbed and re-radiated by the atmosphere is greater than during clear, dry conditions and the ground temperature will consequently be warmer at night. See Table 2 and Fig. 1(c). The moisture content of the air also affects sub-zero temperatures near the ground by another mechanism. As the air temperature drops to near 0°C during the night, the moisture content of the air will rise. Water vapour in the air may condense on the ground forming dew and freeze if the temperature falls below 0°C. The ice visible on the ground is characteristic of a "white" or "hoar frost". These condensation and freezing processes are exothermic and the drop in air temperature is
Figure 1. The energy balance of the soil surface.
(a) during the day – positive energy balance
(b) during the night – negative energy balance
(c) during cloudy or smokey conditions at night.

$S^+ =$ solar radiation
$S^\uparrow =$ reflected solar radiation
$L^+ =$ terrestrial thermal radiation
$L^\uparrow =$ atmosphere thermal radiation

$E =$ evaporative heat loss
$G =$ conduction of heat in soil
$C =$ convection heat exchange
Figure 2. Temperature - height profiles which form
(a) during the day and at night
(b) during windy conditions.
halted while they occur. When the moisture content of the air is low, very little dew or ice is formed and the air temperature can continue to drop relatively uninterrupted. This type of frost is called a "black frost" and they are generally colder than "white frosts". The term "black frost" reflects the colour of vegetation which has been damaged by frost and subsequently infected with bacteria and fungi.

1.1.6 Seasonal Weather Patterns - In Mediterranean climates, low minimum temperatures are more common during the colder months of winter despite the higher incidence of clear, dry and still conditions experienced during warmer months. This is because of the seasonal weather patterns. During winter extremely cold and dry air is transported behind polar fronts from over the Antarctic or Artic to an area, often causing widespread frosts. These frosts are termed "freeze frosts" and are more common nearer the poles. "Freeze frosts" are not necessarily independent of "radiation frosts" and sub-zero temperatures usually develop due to the combination of the influx of cold air and the radiative cooling of the ground at night.

Minimum temperatures near the ground have been predicted using meteorological observations of cloudiness, wind speed and dewpoint depression (Goldsworthy & Shulman, 1984). We can conclude that in the Mediterranean climates, temperatures near 0°C occur over widespread areas at night during winter weather patterns which cause the influx of polar air and clear, dry and still conditions.

1.2 Landscape Aspects

In Southern Queensland minimum temperatures varied by up to 7°C depending upon position within the landscape (Woodruff, unpublished data). While the formation of frosts requires certain meteorological conditions, it is the effects of the landscape which ultimately determine which sites experience the lowest temperatures.

1.2.1 Topography and Aspect - Cold air tends to flow down slopes, following drainage lines and pooling in lower flats and basins. This type of air movement is called a "katabolic" air flow. In general katabatic air flows are light, but they may attain considerable speed if the slope is steep and smooth. At night air temperatures are lower at low altitudes within most landscapes because of the drainage of cold air. However, cold air may collect above midslope barriers against the flow of cold air (such as tree or fence lines), and frosts are more common in such areas.

Slopes with a southerly aspect receive less solar radiation than slopes facing north because of the smaller angle of incidence of the sun's rays and hence they are heated less during the day and are less able to compensate for the loss of thermal radiation during the night. Slopes facing east will receive the morning sun earlier than slopes facing west but they will also be shaded earlier in the afternoon. Hence east and west facing slopes receive the same amount of solar radiation and have similar energy balances.
1.2.2 **Ground Properties** - The amount of heat stored and the ability of the ground to absorb, store, conduct and radiate this thermal energy will affect the occurrence of frost.

Soils with low heat capacity and conductivity characteristics will favour lower minimum temperatures at ground level (Geiger, 1965). During the day, dark soils with high clay and moisture contents and a high bulk density will absorb more solar radiation to a greater depth than light soils with low clay and moisture contents and a low bulk density. Soils which absorb a large amount of heat during the day will also effectively conduct heat towards the cooling soil surface at night. The soil surface and air at ground level will not become as cold during the night in comparison to a soil with low conductivity characteristics. Hence, excluding all other factors, frosts will be more frequent and severe on sandier, light-coloured soils than on the darker coloured, loam and clay soils.

Ground cover will reduce the diurnal fluctuation of soil temperatures. The absorption of solar radiation by the soil during the day is reduced if it is shaded by ground cover (such as a crop or weeds). At night, ground cover also insulates the warm soil from the cold air above the ground cover, such that the transfer of heat from the soil to the air is reduced. At night, the air above shaded ground will be cooler and this is partly why white frosts occur more often on grassed areas than on bare soil.

1.2.3 **Vicinity to Heat Sinks** - Buildings, roads, trees and water bodies are capable of absorbing thermal and solar radiation during the day and releasing it to adjacent areas at night in the same way that the soil absorbs and releases energy. The close proximity to such heat sinks can reduce the occurrence of frost. Temperatures recorded in major country centres will be significantly higher than those in the field because of the high density of heat sinks in a townsite. Frosts are rarer near the coast partly because of the warming effects of the ocean at night.
2.0 PLANT ASPECTS OF FROST DAMAGE

So far we have only described the physical mechanisms which combine to form sub-zero temperatures near the ground. It is important to understand the way plants react to these conditions.

2.1 Ice Formation in Plants - As the temperature of plant tissue drops below 0°C, ice does not form spontaneously but rather the tissue tends to drop to variable and somewhat unpredictable temperatures.

2.1.1 Supercooling and Ice Nucleation - Pure water will "supercool" to below -30°C without freezing under certain conditions. At about -40°C random grouping of water molecules instantaneously trigger the homogenous formation of ice (Bigg, 1953). At warmer temperatures, non-aqueous catalysts known as ice nuclei, order water molecules into an ice-like lattice and initiate the heterogenous formation of ice. In the case of inorganic salts, water molecules are aggregated onto the face of fractured crystals with lattice structures similar to ice (Camp, 1965). Ice nucleators vary in their nucleating ability. Internal ice nuclei which are present within wheat tissue are active at temperatures 1-2°C lower than nuclei present on the external surfaces (D. Woodruff, personal communication). It is thought that when present and effective, external ice nucleators initiate the external formation of ice on the plant surface. The position at which freezing occurs moves along leaves and stems in an "ice front". These fronts may enter the plant tissue at points on the plant surface (depending on the surface properties) and initiate internal freezing. Alternatively, if the external ice fronts fail to enter the plant tissue and the temperature continues to fall, internal nucleators will eventually become effective.

2.1.2 External Ice Nucleators - Atmospheric ice nucleators (windblown soil particles, particularly clay minerals) were once considered to be the sources of external ice nuclei on plants, however the laboratory experiments of Marcellus and Single (1976) suggest that ice nucleation on leaves by air-borne particles is unlikely. Recent research reviewed by Lindow (1983) has focused on the search for biological sources of ice nuclei on plants. Several bacteria commonly found on plant surfaces (including Pseudomonas syringae) are capable of initiating freezing in water at temperatures as high as -1°C whereas atmospheric nucleators are claimed to allow water to cool to about -10°C before initiating freezing. It is thought that an outer membrane protein of these nucleating species is involved in ice nucleation. Bacterial varieties which do not possess this membrane protein have been produced by genetic engineering and they do not demonstrate the nucleating ability of those which are naturally occurring. The biological ice nucleation theory is the subject of some scepticism since it fails to explain why ice forms on surfaces which don't support bacteria such as car windows.
2.1.3 **Internal Freezing** - The highest temperature at which freezing can occur within plant tissue is partly determined by its water potential or moisture status. The freezing point drops about 1°C for each 12 bar drop in water potential in the range of 0-10°C (Maylands and Cary, 1970). When ice nucleation does occur in plant tissue it usually first takes place in the extracellular spaces where water potentials are generally less than those within the cell. It follows that plants which have undergone a period of moisture stress will be less susceptible to freezing because of the lower water potential of their tissues when compared with unstressed plants. Similarly, the nutritional status of the plant will affect its freezing point since a plant with a high nutritional status will have cells with a high concentration of solutes and a depressed water potential.

2.2 **The Effects of Freezing on Plant Tissue** - The two types of freezing injury result from differences in the rate of cooling and the cold tolerance of the plant.

2.2.1 **Dehydration** - Slow rates of cooling cause "equilibrium freezing" within plant tissue. As soon as extracellular ice appears in plant tissue the cells begins to dehydrate because of the negative water potential gradient between ice and water at the same temperature (Olien, 1981). When the formation of ice in the extracellular spaces is slow, the protoplasm can remain supercooled and equilibrate to the new extracellular conditions. Cell death is avoided. Frost hardy plants can withstand temperatures of about -10°C, equivalent to dessication stresses of -100 bars (Maylands and Cary, 1970). The long term consequence of equilibrium freezing is cell death probably caused by a reduction in cell volume and surface area, an increase in the concentration of solutes, the precipitation of some salts resulting in pH changes and the removal of water from macro-molecules (Steponkus, 1978). Damage can also occur during "equilibrium thawing".

2.2.2 **Mechanical Disruption** - Faster rates of cooling result in the more injurious "non-equilibrium freezing". Ice crystals enter cells causing the disruption of the plasma membrane or alternatively, large masses of ice may form along cell walls resulting in cell separation (Olien, 1967). The mechanical disruption of plant cells causes the darkened, water soaked, flacid appearance which characterises the symptoms of freezing damage after thawing has occurred. While supercooling of tissues is an effective mechanism for avoiding freezing damage, once freezing is initiated it proceeds at an extremely rapid rate in intra and extracellular spaces. Frost tender plants can only withstand a few hours at about -3°C before ice enters cells causing permanent damage. The amount of tissue injury caused by mechanical disruption can be assessed by measuring the loss of electrolytes from the ruptured cells (Flint et al., 1967).
2.3 Temperature Profiles in Cereal Crops

When a cereal crop is growing in the soil, the temperature - height profile of the air differs to the profile which develops over bare soil. The crop reduces the amount of solar radiation absorbed by the soil during the day and also insulates the air above the crop from the warming effects of the soil at night. The surface of the crop canopy is the primary radiating surface at night and because the plant has a smaller heat storage capacity than the soil, it cools at a greater rate.

It was shown by Marcellus and Single (1975) and Rowley (unpublished data) that under conditions of radiation frost the crop ears become 0.5-1.5°C colder than the adjacent air. This air is cooled by the crop surface, forming a layer of cold air over the crop (negative inversion) as illustrated in Fig. 3. The temperature of the air near the crop surface becomes 1.0-1.5°C lower than that of the air near the surface of the bare soil under the same conditions. Nearer the soil surface, the crop is warmed by intercepting the thermal radiation emitted by the soil and also by direct conduction via roots and stems.

The convection of air within the whole canopy should prevent the formation of static layers of air but it appears that the radiation flux from the crop surface is large enough to maintain the negative inversion profile. The degree of the negative inversion probably increases with increased plant density and plant height.

![Temperature-Height Profiles Diagram]

Figure 3. Temperature-height profiles which form in a crop into head during radiation frosts.
2.4 Wheat Development and Frost Injury

The susceptibility of wheat to freezing injury increases with its development. Prior to imbibition, a dry seed is capable of surviving exposure to -196°C (Andrews et al. 1974) whereas the lethal temperature at about anthesis can be about -2°C. The lethal air temperature of a crop at a specific stage of development is not constant and may vary as much as 2-3°C (Single, 1984). Much of the research into lethal temperatures has assumed that injury is a function of temperature alone and fails to consider other factors, primarily moisture status and the presence of nucleators. This may help to explain the variability of the results of such work.

2.4.1 Seedling and Tillering Growth - During the seedling and tillering stages of development, the wheat plant is rarely killed by frosts. At approximately -2°C, freezing will initiate from external nucleation points on leaves and make its way in a front, travelling internally and externally down the leaves and eventually into the stem. Stem and leaf tissue is relatively cold hardy because it possesses large intercellular spaces through which the ice fronts can pass. Despite suffering some dehydration leaves will recover if the freezing period is short and ice is confined to extracellular spaces (Marcellos, 1977). Growth at low temperatures and short photoperiods increase the plant's tolerance of ice within its extracellular spaces, the process being termed "cold hardening" (Marcellos and Burke, 1979).

At severe temperatures (i.e. about -6°C for spring wheats) ice will enter plant cells and the leaves may become blighted. However, the plant is able to regenerate leaves from its apical tissue in the crown region, which remains below or within a few centimetres of the soil surface. Because of the warming effects of the soil, this tissue will remain unaffected by moderately severe frosts during seedling and tillering growth. The apical tissue will only be killed at this stage of development by temperatures below about -10°C.

2.4.2 Stem Elongation and Booting - During these stages of development the actively growing apical and floral tissues are forced away from the soil surface towards the top of the crop canopy and its associated cold air. Hence, the susceptibility to freezing of these tissues and plant death increases during stem elongation and booting. The apical and floral tissues are considered cold tender because they lack large intercellular spaces and ice can progress from cell to cell via protoplasts causing rapid death (Marcellos, 1977). The increasing height and density of the crop canopy during stem elongation and booting would also cause colder air temperatures above the crop.

Apical and floral tissues remain supercooled without the formation of ice during mild frost events. Leaf sheaths prevent the initiation of ice crystallization from external nuclei and stem, rachis and rachilla nodes provide an
internal barrier against the passage of the ice front from the stem (Marcellos and Single, 1984). At temperatures below about -4°C these internal barriers begin to breakdown. Ears that have been frosted before emerging from the boot are characteristically blighted at the base since the damaging ice front travels up the stem to the ear. All developing floral parts are affected, including glumes and lemma.

Injury to stems may also occur below -4°C and it is characterised by various degrees of discoloration and distortion of the nodes and internodes. These symptoms are not always associated with damage to floral parts (Banath & Single 1976). Observations in the field and laboratory show that grain size and quality are not seriously affected by stem freezing alone. However, grain numbers may be reduced and ears lost through lodging (Banath and Single, 1976).

2.4.3 Post Ear-Emergence - Once the flag leaf opens and the spike emerges, the "cold tender" ear is then susceptible to freezing directly initiated by external nucleation points. Only the anthers and ovary may be frozen and the resulting head appears normal but no grain will develop. Unlike damage caused while the ear is still in the boot, grain is affected at random points along the ear. Grain filling can be prematurely terminated by freezing until the development of hard dough or when the moisture content of the grain is not high enough for the tissue to freeze (Single, 1984).

The lethal temperature following ear emergence varies considerably in the field and in the laboratory. Lethal temperatures vary from -1.8°C (Marcellos and Single, 1974) to -5°C (Single, 1961) in the laboratory. Artificial ice nuclei have gone some way toward simulating natural conditions and it appears that lethal temperatures in the field are at the upper end of the range recorded in laboratory. In the laboratory experiments of Marcellos and Single (1984), seed mortality initiated at about -4°C and reached 100% at about -5°C.
3.0 FROST DAMAGE TO WHEAT IN WESTERN AUSTRALIA

It is important to determine what factors interact to cause frost damage to cereals in Western Australia and which of these can be manipulated to reduce the amount of damage. Let us firstly consider what physical conditions are experienced in Western Australia and the way in which wheat grown in Western Australia interacts with these conditions.

3.1 Physical Conditions in Western Australia

3.1.1 Temperatures in Western Australia - Much of Southern Australia experiences a classical Mediterranean environment with cold, wet winters and hot, dry summers. Temperatures are generally lowest during July in the Eastern States whereas August is the coldest month in the south-west of Western Australia. See Fig. 4. The lowest minimum temperatures experienced in the West Australian wheatbelt are milder than those experienced in the Eastern States. Screen temperatures below -3°C are very rarely recorded in Western Australia. At the Wandering weather station, the average number of days during which the temperature drops below -3°C in July is 0.07. The comparable figure for Wagga Wagga (N.S.W.) is 1.01. See Fig. 5.

*Figure 4. The mean monthly minimum temperatures at Corrigin, Tamworth, Wagga Wagga and Wandering. Data from the Bureau of Meteorology - Meteorological Information Services Section.*
3.1.2 Meteorological Conditions During Frosts - In general, frosts occur between the months of May and October in Western Australia's southwest. During winter, cold fronts bring cold air from over the Antarctic to the lower portion of the State. Following the passage of the cold front toward the east, a high pressure system becomes located over the south-west of the State. See Fig. 6. This sometimes causes cloudless, dry and still nights, during which the loss of thermal radiation by the ground is unimpeded and the formation of the inversion profile is not disturbed by air movements. These conditions are ideal for the development of radiation frosts.

3.1.3 Measuring Frost Risks - The average frequency of frosts over the year will follow a mathematical distribution and a useful measure of frost risk is the probability of the occurrence of a frost event during a particular month or week. However, accurate measures of the probability of frost occurrences which have the potential to cause damage to crops are very difficult to determine.

The incidence of frosts was analysed in the Bureau of Meteorology Regional Surveys (Anon., 1964) and by Perry (1971), however both sources used screen temperatures below +2.2°C (36°F) to define potentially damaging frosts. Even while compensating for the fact that screen temperatures taken at the Bureau of Meteorology (MET) weather stations are usually higher than those of crops in the field, this definition
seems to overestimate the occurrence of damaging temperatures. At its most susceptible stage of development, wheat will be damaged by temperatures below about $-2^\circ\text{C}$ in the field. This critical temperature probably corresponds to about $0^\circ\text{C}$ at a MET station depending upon the location of the station relative to the field.

The observation of frost on the ground (white frost) at MET stations is also an inaccurate overestimate of damaging temperatures. Ice which develops on the ground and on the surface of plants can act as an insulator against the further loss of heat. Also, very low temperatures are usually experienced when the air moisture is not high enough to allow the formation of ice on the ground (black frosts). The frequencies of temperatures below $2.2^\circ\text{C}$ and days when white frosts are observed are greater than the frequency of temperatures below $0^\circ\text{C}$. See Fig. 7.
Figure 7. The mean number of days per month when temperatures fall below 2.2 and 0.0\degree C and when white frosts are observed at Wandering. Data from the Bureau of Meteorology.

3.1.4 Landscape Effects on Western Australia – In Western Australia the landscape plays an important role in determining which sites within a region experience frost damage to wheat. Frosts are mild in Western Australia and the drainage of cold air to low sites in the landscape is often necessary to cause damaging temperatures at these sites. If frosts were very severe (i.e. 8\degree C below the critical temperature for the crop) the effects of landscape would be masked and damage would occur uniformly over the landscape. A survey of farmers affected by the 1985 frost showed that 35% of the area affected was on flat ground and 51% on lower slopes (Loss, unpublished data). In the western regions of the Great Southern, the landscape is considerably more undulating than in the eastern regions, hence the formation of damaging temperatures tends to be more localised and frequent.

3.2 Temperature and Plant Interactions

3.2.1 In Western Australia – The majority of frost damage which is reported in Western Australia occurs at about the time when the crop is most susceptible to frost, following or at about the time of ear-emergence. Very little damage is reported before September despite the higher frequency of sub-zero temperatures recorded in screens because frost events are not severe enough to cause damage to crops during their cold hardy stages of development. The susceptibility of wheat to frost damage and its relationships to plant development and temperature in Australia can be illustrated as in Fig. 8(a).
3.2.2 In High Northern Latitudes - The interaction between temperature and the development of spring wheats in Australia, contrasts the interaction of wheat with the temperatures of Northern Europe and Canada as illustrated in Fig. 8(b). In high northern latitudes, winter wheats survive air temperatures which are 4-6°C colder than the extreme temperatures experienced in Western Australia. This is only partly because of an inherent tolerance of colder temperatures. Winter wheats planted in autumn survive very cold temperatures during winter while at the cold hardy, seedling stage of development. The wheat seedling undergoes a period of gradual cold hardening during early winter and it may be protected under a layer of snow against the extreme cold of mid winter. The variety Mironowskaja 808 has been reported to survive air temperatures as low as -16°C during the seedling and tillering stage of development (Johansson, 1970). Because of the strong vernalisation requirement and photoperiod response of winter wheats, further development does not occur until the more favourable temperatures and longer photoperiods of spring. Flowering occurs in mid-summer.

3.3 Historical Occurrences of Frost Damage - In 1986, extensive requests were made to farming communities for actual dates when frost caused damage to cereal crops in Western Australia. Only 15 useful dates were received. This poor response is probably because farmers often do not realise crops had been damaged by frost until after harvesting commences and poor yields are obtained.

3.3.1 Frequency of Damage - Of the 15 dates received, six were from the 1980s, three from the 70s, three from the 60s, two from the 50s and one from 1934 (See Table 3). It was apparent from these reports and from discussions with farmers that the frequency of the occurrence of frost damage in the Great Southern had increased in the last decade, with eight of the ten years having some frost damage reported. Before 1971 the next nearest report of frost damage was in 1954. This situation seems to contrast that in the eastern wheatbelt, where the last serious report of frost damage was in 1969.
Figure 8. An illustration of the relationships between the development of wheat, extreme minimum air temperature and the minimum temperature which will be lethal to the growing point of the plant.
(a) In Western Australia (spring wheats)
(b) In Northern Europe (winter wheats).
<table>
<thead>
<tr>
<th>Year</th>
<th>Date</th>
<th>Districts</th>
</tr>
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<tbody>
<tr>
<td>1985</td>
<td>Oct. 22</td>
<td>Narrogin, Katanning, Northam (S)</td>
</tr>
<tr>
<td>1984</td>
<td>Sept. 3</td>
<td>Katanning</td>
</tr>
<tr>
<td></td>
<td>Sept. 21</td>
<td>Salmon Gums</td>
</tr>
<tr>
<td></td>
<td>Oct. 30</td>
<td>Pingelly</td>
</tr>
<tr>
<td>1982</td>
<td>Oct. 26</td>
<td>Narrogin, Katanning</td>
</tr>
<tr>
<td>1981</td>
<td>Oct. 18</td>
<td>Narrogin, Katanning, Northam (S)</td>
</tr>
<tr>
<td>1979</td>
<td>Sept. 27</td>
<td>Narrogin, Salmon Gums</td>
</tr>
<tr>
<td>1977</td>
<td>Sept. 11</td>
<td>Narrogin, Katanning</td>
</tr>
<tr>
<td>1971</td>
<td>Oct. 11</td>
<td>Narrogin, Merredin</td>
</tr>
<tr>
<td>1969</td>
<td>Aug. 20-22</td>
<td>Merredin</td>
</tr>
<tr>
<td>1968</td>
<td>Oct. 6</td>
<td>Merredin (S)</td>
</tr>
<tr>
<td>1960</td>
<td>Sept. 23</td>
<td>Merredin</td>
</tr>
<tr>
<td>1954</td>
<td>Sept. 3</td>
<td>Merredin</td>
</tr>
<tr>
<td></td>
<td>Oct. 7</td>
<td>Narrogin, Katanning, Salmon Gums (S)</td>
</tr>
<tr>
<td>1934</td>
<td>Sept. 13</td>
<td>Merredin</td>
</tr>
</tbody>
</table>

(S) = severe frost causing widespread damage
3.3.2 Factors Affecting Frequency - In recent years cropping has been more profitable than livestock enterprises in Western Australia and the area of wheat sown has increased by about 60 per cent in the last decade. This is probably causing an increased exposure to frost especially where crops are planted in the frost susceptible sites within the landscape and in regions of the State which would have been avoided previously. In the area of the southwest, west of the Great Southern Highway, higher wheat yields are obtainable than in other parts of the wheatbelt because of more fertile soils and higher rainfall. However, the risk of frosts is also greater in this hillier country.

Ear-emergence has been recognised as the critical development phase after which wheat becomes highly susceptible to freezing during the frosts experienced in Western Australia. With the recent emphasis on early sowing and the release of short season varieties bred for the northern wheatbelt, it is likely that ear-emergence is now occurring earlier during a period of greater frost risk, than a decade ago.
4.0 MINIMIZING FROST DAMAGE IN WESTERN AUSTRALIA

Frost damage to wheat can be minimized by (i) changing the physical conditions experienced by the plant and (ii) improving the plant's tolerance of low temperatures either by manipulating the plant's development relative to the physical conditions, or by improving the plant's resistance to ice formation and freeze injury at about ear emergence. The interaction of these factors is illustrated in detail in Fig. 9.

4.1 Manipulating Physical Conditions

In horticulture, there are several control measures used against radiation frosts, which rely on a method of manipulating the physical environment within the crop to reduce the amount of frost damage.

4.1.1 Sprinkler Systems - This system relies on maintaining water on the surface of the plant. The freezing of water is an exothermic process and while it occurs on the plant surface, the temperature of the plant remains near zero, even when the air temperature is 3 or 4°C lower. Wetting the soil also increases the conduction of heat to the soil surface.

4.1.2 Wind Machines - The idea of this system is to force convection to occur thereby mixing the cold air near the ground with the air of the warm inversion layer which rose during the day.

4.1.3 Smoke, Fog and Aerosol Clouds - In this system an artificial cloud is produced over the crop reducing the amount of radiation lost by the crop and the ground in the same way that natural cloud cover reduces the loss of radiation at night.

4.1.4 Heating Pots - Pots containing burning fuel can be placed within the crop to warm the air and to induce convection with warmer upper layers of air.

4.1.5 Soil Management - During times of high frost risk, an attempt is made to keep soils moist and compacted, to improve heat conduction to the surface at night, and free of weeds so that the soil is not shaded during the day.

Frost control measures used for horticultural crops have had varying degrees of success, however their application to broad acre crops would be impractical and very uneconomic. The temperatures experienced by wheat crops could perhaps be increased by as much as 2-3°C by manipulating plant height and crop density. This would significantly reduce the risk of frost damage in Western Australia.

4.2 Manipulation of Development - Flowering or ear emergence has been recognized as the development phase after which the crop becomes highly susceptible to frosts experienced in Australia. Hence, the timing of flowering relative to the occurrence of damaging temperatures is a critical factor in determining how much frost damage occurs in Western Australia.
Figure 9. The Interaction of Factors Affecting the Amount of Frost Damage in W.A.

- Physical Factors
- Genetic Factors
- Physical Factors Controlled by Man
4.2.1 **Optimum Flowering Periods** - Numerous studies have shown that yield rapidly diminishes for each week of delay in anthesis past an optimum date (i.e. Doyle and Marcella, 1974; Fischer, 1979; Kohn and Storrier, 1970). The earliest date most suitable for flowering and the beginning of grain filling is set by the last occurrence of frost. The latest date is determined by high temperatures and water availability during grain filling. Hence, it is possible to identify an optimum flowering period for a specific region from meteorological records of frost, rainfall and temperature (see Fig. 10). This optimum flowering period will represent a compromise between yield losses caused by frost and drought. In some marginal areas, it may be that frosts occur late in the season, after the last effective rainfall and the manipulation of flowering time will only determine whether the crop will yield poorly because of frost or moisture stress in the average year.

![Effective Rainfall Diagram](image)

**Figure 10.** Factors restricting the time of flowering in W.A.

4.2.2 **Manipulating Flowering** - Flowering time can be manipulated by altering the time of sowing and/or the genetic rate of development of the crop (i.e. the genetics of phenology). The meteorological variables, photoperiod and temperature which largely control the rate of development of a particular genotype can be considered to be constant for the "average season at one location". The desire to maximise the length of growing season and improve yields, coupled with an improved technical ability has brought about an emphasis on
early sowing. The estimate of the loss of yield due to delayed planting used by MIDAS (Model of an Integrated Dryland Agricultural System) is greater than 10 kg/ha/day (M. Ewing, personal communication). The timing of the break of the season is the ultimate determinate of how early a farmer can sow, and since it is a meteorological factor it can be also considered constant in the "average season for one location". Hence, in Western Australia, the time of flowering is largely determined by the genotype. The introduction of genotypes which flower within a region's optimum flowering period will result in higher yields in the long-term.

4.2.3 Seasonal Flexibility - Until now, I have only considered the average season. Avoiding frost damage by manipulation of flowering will also involve a flexibility of management to adapt to the current season. This concerns the timing of the break of the season and the selection of a variety that will flower during the optimum period. If the break of the season is early, yields could be maximised without increasing frost risks by sowing early with a longer season variety. In the eastern wheatbelt some farmers take advantage of an early break by sowing with Bencubbin, a mid-maturity variety released in 1930. Early sowing with recommended short season varieties (i.e. Bodallin, Gutha and Canna) would increase the risk of frost damage since flowering would occur in a time of greater frost risk.

4.2.4 Localised Optimum Flowering Periods - In Southern Queensland, minimum temperatures vary up to 7°C because of the effects of landscape within a region (Woodruff, personal communication). Given this variation in the physical conditions experienced by crops within a region, it should be possible to manipulate development according to the constraints of the physical conditions of local sites, so that frost damage is minimized. The frost risks of each paddock on a farm can be determined and optimum flowering periods calculated. The amount of frost damage will be minimised by planting after a particular date, depending upon the variety sown and the paddock's frost risk. If the frost risk of a paddock is very high it may be more worthwhile to use the paddock for some enterprise other than wheat or barley production, which is less susceptible to frost damage.

4.3 Resistance to Ice Formation and Freeze Injury - A plant's resistance or tolerance of cold temperatures at a about ear emergence will also affect the amount of damage caused by frost.

4.3.1 Plant Breeding - The development of varieties which are tolerant to frost in the heading stage is a method of reducing the amount of frost damage and it would also permit earlier flowering and higher yields. The development of totally "frost resistant" varieties is very unlikely although crosses involving Afgan varieties have led to the development of varieties which are capable of surviving with only minor damage, freezing conditions that cause 100% loss of tillers in commercial varieties (Single et al. 1970). The progress
of breeding for resistance to freezing after ear emergence is slow since it is not a character which can be measured on a single spike or plant. It can only be defined as the average reaction of a population of plants to a number of stresses. Heavy glaucousness, the absence of awns and good rachis and rachilla resistance are thought to provide resistance to the external and internal formation of ice in floral tissues. (Marcellos and Single, 1974).

4.3.2 Cryoprotectant Sprays - Cryoprotectant sprays are available which increase the plant's tolerance to frost conditions by reducing internal freezing. These were originally simple chemical surfactants but recent work in the U.S.A. has been devoted to suppressing biological ice nucleators. Bacteriocides appear to be effective in reducing frost damage when applied before bacterial populations develop naturally on plants. Genetically engineered bacteria which lack the nucleating ability have been applied to plants in an attempt to reduce the concentration of biological nucleators by competition with the naturally occurring bacteria (Lindow, 1983). Significant results have been claimed on corn and potato seedlings and almond and pear trees but whether such treatments are effective is a subject of scepticism. The effectiveness of cryoprotectants on cereal crops has yet to be assessed.
5.0 RESEARCH DIRECTIONS

Laboratory experiments of Marcellinos and Single (1984) demonstrated and field observations suggest that seed mortality can change from 0-100% over a 1°C temperature drop. The large slope of this mortality curve is encouraging to agronomists and breeders alike, since a small improvement in the temperature within the crop or variety resistance to frost, could greatly reduce yield losses within the temperature range of frosts experienced in Western Australia.

5.1 Regional Frost Occurrence

There is firstly a need to accurately determine the risks of frost at different regions of the State at different times of the year. Accurately determining frost risks would allow researchers to assess management options in an objective perspective. Damage to frost can be spectacular and it lives in the memory for a long time. Perhaps the strength of the fear of frosts is greater than it should be for certain parts of the wheatbelt.

Previous analyses of the occurrence of frosts which used +2.2°C as the critical screen temperature appear to be inaccurate. A more accurate estimation of the occurrence of frosts which have the potential to cause damage, would be to identify specific dates of frosts causing damage to crops and correlate these with temperatures recorded at the nearest MET station. A critical temperature could be determined for each station and historical MET records could be analysed to determine the probability of damaging frosts on a regional basis. This analysis is currently being attempted.

5.2 Optimising Varietal Development

There is a need to accurately define the optimum flowering period for a particular region using regional frost occurrences and average rainfall and temperature records. More suitable varieties could then be selected for a particular region based on the region’s optimum flowering period. An investigation is currently being undertaken to accurately define the phenological response of wheats to photoperiod and temperature in Western Australia.

The simple model:

\[ \text{Development Rate} = \frac{1}{\text{Duration}} = b_0 + b_1 (\text{TM}) + b_2 (\text{PM}) \]

(where TM and PM are the mean temperature and photoperiod experienced during the phase of development, and \( b_0, b_1, b_2 \) are the fitted regression coefficients) accounted for greater than 70% of the variation in the duration of sowing to flowering for 92% of 120 wheat varieties tested in 1985. A computer programme has been devised which calculates the regression coefficients from observations of flowering at several selected locations. The programme can then use these coefficients to predict flowering at any other location given the sowing date and the year. In this way plant breeders can select for further testing, breeding lines that will flower within a region's optimum period without actually having grown them in that region. This system reduces the number of sites
at which a line must be tested and allows the testing and selection of a larger number of lines. Hence, the selection of lines which are phenologically adapted for a particular region will be more efficient.

5.3 Local Frost Occurrence

In addition to regional frost risks and probably more importantly, farmers will require some knowledge of the frost risks of individual paddocks. The frost risk of an individual paddock can be determined by measuring temperatures in the paddock for a period of time during which sub-zero temperatures occur and then relating these temperatures to others experienced in the rest of the region. Hence, localised frost risks could be utilized in overall farm planning, so that cropping wheat and barley occurs only at worthwhile low frost risk sites.

A better understanding of the development of radiation frosts in crops and the drainage of cold air within a landscape would lead to a more rapid determination of local frost risk. Farmers should be able to map their property for frost risk on the basis of aspect, soil type, position in the landscape and regional frost risk. The effects of these factors on air temperatures in crops need to be quantified. HCMM (Heat Capacity Mapping Mission) thermal imagery has been successfully used for frost mapping (Kalma et al. 1983).

5.4 Resistant Crops and Varieties

The resistance to frost of alternative crops needs to be quantified and an agronomic and economic assessment of their suitability to frost susceptible sites and regions can be made. From observations in the field it appears that oats is very much more tolerant to frost damage than barley, which is slightly more tolerant than wheat. An increased knowledge of the mechanisms of freezing resistance could lead to the better selection for frost tolerance in wheat breeding programmes.

5.5 Other Agronomic Manipulation

Crops planted with a 54 cm row width are usually 1-2°C warmer than crops with 18 cm spaced rows (D. Woodruff, personal communication). The practical importance of this observation needs to be determined and a better understanding of the effects of crop density and height in relation to the development of radiation frosts is required.

The use of cryoprotectants is worthy of investigation despite the probable reluctance of farmers to purchase and use chemicals. Very little work has been done concerning cryoprotectant application to broadacre crops. Important considerations in such work would include the timing of application and cost.

5.6 Dissemination of Information

It is hoped that a greater interest and understanding of frost damage is generated within farming communities by the dissemination of information. Knowledge of "the current understanding of frost damage" will lead to more informed management decisions and hopefully reduced losses caused by frost damage.
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