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National and regional assessments of crop yield trends and relative production efficiency: Theme 5.1. Land use change, productivity and diversification

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NATIONAL LAND AND WATER RESOURCES AUDIT

NATIONAL AND REGIONAL ASSESSMENTS OF CROP YIELD TRENDS AND RELATIVE PRODUCTION EFFICIENCY

THEME 5.1 LAND USE CHANGE, PRODUCTIVITY AND DIVERSIFICATION

Department of Agriculture
Government of Western Australia

National Land & Water Resources Audit
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THEME 5.1 LAND USE CHANGE, PRODUCTIVITY AND DIVERSIFICATION

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DEPARTMENT OF AGRICULTURE, WESTERN AUSTRALIA

JUNE 2002
## National Land and Water Resources Audit - Theme 5.1 Land use change, productivity and diversification

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EXECUTIVE SUMMARY

As a part of the National Land and Water Resources Audit (NLWRA), Project 5.1 was developed to identify the spatial and temporal trends in land use change, productivity and enterprise diversification within the intensive land use zone of Australia (ILZ). The study reported here assesses productivity increases and production efficiencies across the Australian grain belt between 1982 and 1997 (the audit period). Grain yield comparisons across regions were made with a yield-forecasting model STIN (STress INdex). STIN calculated a moisture stress index, which when incorporated into a multiple regression approach, was able to separate yield variability from technological changes in yield through time, i.e. yield trend. The impact of climate variability on production was assessed with the coefficient of variation in de-trended yields, while water use efficiency (WUE) of crop production was determined from modelled soil moisture and growing season rainfall.

In an earlier report on wheat yield trends and soil fertility in Australia (1950-91) by Hamblin and Kynure (1993), low or static yield trends across many drier areas of the Australian wheatbelt were attributed to low soil fertility, largely related to nitrogen (N). The main factors limiting input of N were poor legume pastures, a low proportion of grain legumes in rotation and inadequate inputs of N fertiliser.

This study finds a period of improvement in cropping performance indicators in most areas. Steeper yield increases and increasing crop diversity occurred through the audit period as farmers addressed financial constraints and sustainability issues. Increased rates of yield improvement were most noticeable in Western Australia, and to a lesser extent in South Australia and New South Wales. During the period, Australia lifted its share of the export wheat market with higher yield increases than other exporting countries. Improved crop productivity coincided with a shift to higher input agriculture (N fertiliser, herbicides), higher yielding varieties (semi-dwarf, disease resistance, long season), and better management practices (better rotations, early sowing, ameliorating soil constraints, minimum tillage and better weed control). The importance of N is confirmed, as regions with increased N supply to crops were most successful at raising productivity and had a positive N balance. Yield variability, the relative profitability of different crops and overall farm profitability were also important factors in influencing regional yield increases.

In relation to wheat, this study finds:

- A recent three-fold increase in national wheat yield trends compared to the previous 50-years. Regionally, highest wheat yield trends (> 60 kg/ha/yr) occurred in south-eastern and north-eastern areas of New South Wales, north-western and south-western Western Australia, wetter districts in South Australia and the south-eastern edge of the Darling Downs in Queensland. Negative yield trends were found in some of the most variable shires of Queensland and South Australia, along with shires in the Murray Mallee (New South Wales) and Hindmarsh shire in the northern Wimmera (Victoria).

- Higher yield trends occurred where farmers addressed a combination of soil constraints, including chemical (nutrient, acidity), biological (diseases, weeds, nematodes) and physical (water storage, infiltration) factors. The best performing shires consistently increased N fertiliser application and crop diversity (pulses, oilseeds, or sorghum), with the latter being important where N-fixation, and/or soil cleansing of root diseases, was beneficial.

- Climate constraints dominated the performance of the Australian grain industry as unreliable rainfall across seasons resulted in yield variability and income risk aversion practises. High yield variability is a major constraint to increased crop productivity as it deters:
  (i) Adoption of non-cereals. If the coefficient of variation (CV) of wheat yields (across seasons) exceeded 0.35, there was a small increase (even decrease) in crop diversity, whereas a 10-25 per cent increase in diversity generally occurred when
the CV was less than 0.2; and
(ii) High application rates of N fertiliser. Low to negative yield trends occurred over large areas of Queensland, northern Eyre Peninsula (South Australia), northern Victoria and central NSW where yield variability was very high and risk management kept N application rates very low.

- The most profitable farm businesses in the 1990s had high productivity increases, low yield variability and high cropping intensity. Higher cropping intensity did not seem to impact negatively on crop performance as higher trends have occurred in some of the most intensely cropped zones where cropping intensity has increased (more non-cereals in rotation). Farm business profits appear linked to the adoption of new farming technology and the amount of inputs applied.

- Highest percentage increases in wheat yields generally occurred across Western Australia and were related to widespread adoption of a new agronomy package, incorporating new varieties and better management. The change to a wheat/lupin rotation substantially increased wheat yields on infertile soils. Low yield variability and many good seasons (absence of major droughts) encouraged a high yielding agricultural farming system.

- In South Australia, wheat yield trends were the most closely related to rainfall, with wetter districts (> 400 mm annual rainfall) consistently having yield increases greater than 45 kg/ha/yr, and drier districts consistently lower than 30 kg/ha/yr. Drier districts with greater yield variability were slower to adopt break crops, had greater root disease and applied little N.

- Victorian wheat yield trends were lower than other regions in southern Australia and coincided with a negative N balance across the main cropping areas. Despite a 10-35% increase in the proportion of pulses and oilseeds in rotation in southern Victoria, wheat yield trends suffered as grain legumes in this region leave little residual N, better land was planted to “cash” legume crops, and a decline in long fallowing reduced the amount of soil moisture carrying through to wheat crops.

- In south-eastern New South Wales, very large yield trends coincided with some of the largest application rates of lime and adoption of canola, better grass weed control, and use of higher yielding varieties in wetter areas. Very low wheat yield trends in northern New South Wales were reversed, as farmers:
  (i) substantially increased application of N fertilisers and reversed soil fertility decline;
  (ii) improved fallow and weed control management; and
  (iii) increased summer cropping (sorghum) which forms a break crop reducing root disease. Increased cash flow from successful summer crops (sorghum/cotton) meant farmers were able to spend more on inputs for winter crops. Also, the realisation that applied N can carry over from a low yielding crop to the next season has reduced the downside risk of high input costs and losses in dry seasons.

- Queensland wheat yield trends were severely affected by droughts of the early 1990s, low N inputs, low adoption of legumes and oilseeds and an increase of root diseases coinciding with increased stubble retention/minimum tillage.

- High water use efficiencies (WUE) were generally found in southern States where soils had good water-holding capacities, rainfall was reliable between June and September, and yield variability was low. Subsoil restrictions to roots, root diseases, nutrient deficiencies and extreme climate variability appear to substantially reduce WUE in north-eastern regions. High amounts of drainage and waterlogging on duplex soils
reduce WUE in wetter districts of Western Australia, while poor water-holding capacities, highly sodic subsoils, and water repellency appear to reduce WUE in the Eyre Peninsula and the upper south-east of South Australia.

In relation to the other winter cereals and sorghum, this study finds:

- Barley yield trends were generally lower than wheat, attributable to less N fertiliser, as price premiums were offered for malting barley which required lower protein/N content in the grain. Trends showed the same regional patterns as wheat, but were better than wheat in southern Victoria and southern Western Australia where barley handles waterlogging and frosts better.

- Oats (and other cereals) had lower trends than wheat, but did better in wetter/cooler environments where special contracts for milling oats were offered. Trends were highest in southern Australia and negligible in northern areas where they are only grown in small amounts.

- Summer sorghum yields improved dramatically in northern NSW in the 1990s in conjunction with a large increase in N application, whilst serious droughts restricted trends in Queensland.

- The regional pattern of WUE for barley, and oats and other cereals tended to match wheat, but were mostly lower, especially in more northern and more arid regions. There was a steep decline in sorghum WUE as one moves inland from the Darling Downs and Liverpool Plains to regions in the western cropping areas of Queensland and northern New South Wales.

With Australian growers shifting to higher input farming, there is now a greater vulnerability to financial losses in poor seasons, and therefore a greater need for:

(i) accurate seasonal forecasts with good lead times and tactical decision support tools to assist in managing crop selection and inputs in relation to climate risks;

(ii) better allocative skill (mix of crops in relation to prices) in decision making; and

(iii) increased N use efficiency through tactical and targeted management (e.g. precision agriculture) and more nutrient responsive varieties.

Advances made in the last 20 years suggest that the sustainability of farming practices has improved in the Australian cropping sector. If improvements continue in varieties, management, and nutrient use, yields and WUE should improve. To obtain this, high levels of agricultural research appear necessary. However, regional factors influencing sustainability and productivity, highlighted in this report and the NLWRA (2001), need to be addressed.
1. INTRODUCTION

1.1 Terms of reference

The services to be delivered by the consultant are:

1. National and regional assessments of relative production (yield) efficiency for wheat and other cereals by providing estimates of biological production potential based on seasonal climatic conditions, compared with actual production values for selected historical dates, between 1982 and the present.

- In collaboration with BRS and ABARE, develop maps and temporal yield trends, for the period 1982/83 to 1997/1998, using 1996/97 as the baseline, at SLA (Statistical Local Government Area) level of resolution across the Intensive Landuse Zone (ILZ)\(^1\) for commercial yield of:
  - wheat;
  - other cereals (as grouped together on a commodity-land use basis, in the National Land Use Mapping project BRR5, of the NLWRA);
  - and estimated (projected) figures for the above, for 2000/01, using appropriate crop forecasting models based on rainfall, ABS surveys and the ABARE econometric model (prices anticipated);
  - using a rainfall-based model compute the ‘water use efficiency’\(^2\) of selected crops over the period 1982/83 to 1997/98 to provide a first order, gross relationship for yield and rainfall per SLA, in collaboration with BRS statistical support.

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\(^1\) The ILZ boundary will be that identified by the Audit managers to accord with the consensus across all Audit projects if possible. However, as Project 5.1 has a longer historical time frame than most projects, during which period there has been considerable variation in the extent of the ILZ in some regions, the project team should have a considerable input into the SLAs which are included.

\(^2\) ‘Water use efficiency’ here is considered to be equated with ‘production efficiency’ per mm rainfall (as in the Western Australian Department of Agriculture’s models STIN and PYCAL) based on calculations of stored water and growing season rainfall. It will not extend to identification of the effect of seasonal heat sums, frost damage, waterlogging and other climate-related production constraints.
1.2 Background

Australian crops are grown in a variable semi-arid environment on soils with variable structure and fertility. Yield variability is amongst the highest in the world (Calderini and Slafer 1998) and is strongly influenced by the El Nino-Southern Oscillation phenomena which amplifies climate variability (Nicholls 1990). Many soils have very low nutrient concentrations, poor water-holding capacities and poor structure. These climate and soil constraints place severe limitations on management options and discourage high input farming practices that have been associated with higher yields in other countries (Pardey et al. 1999).

Consequently, Australia has had one of the lowest rates of wheat yield improvement in the world (Kogan 1986; Hamblin and Kyneur 1993), with some suggesting that yields had levelled off prior to the early 1980s (Sakamoto et al. 1980; Kogan 1986). In a comprehensive study of regional wheat yields prior to 1992, Hamblin and Kyneur (1993) found very low trends in drier inland areas in a wide arc running from north-eastern Western Australia, most of South Australia, most of Victoria, northern New South Wales and south-western Queensland. From the early 1980s, Hamblin and Kyneur noticed that yields had started to rise more steeply in areas such as Western Australia which had adopted improved practices, such as incorporating grain legumes in rotation, and applying more N fertilisers. Whilst calibrating crop models at a State-level, Stephens (1995) found the rate of wheat yield improvement increased at a greater rate in Western Australia and South Australia from the mid-1980s. Considerable improvements (up to 80 kg/ha/yr) were found in Western Australian shire wheat yields between 1980 and 1994 (Stephens 1997) and wetter shires of South Australia to 1994 (Black 1998). In north-eastern Australia Cornish et al. (1998) found that wheat yield trends were very low between 1975 and 1993, but were better in south-eastern New South Wales.

Some of these earlier studies used linear or quartic curve fitting procedures to determine trends in yields which can be strongly influenced by high climate variability and sequences of low or high yielding years. The difficulty of curve fitting is highlighted in Figure 1.1 which shows average State and national wheat yields from 1930-2000 with linear trends fitted prior to, and after, the commencement of the NLWRA analysis period, i.e. 1982. In Queensland, the five-year drought between 1991 and 1995 severely affects curve fitting resulting in an artificial downward trend. In contrast, the low variability in yields in Western Australia through the 1980s and 1990s coincided with a sequence of good seasons. Yield variability at a State level in Western Australia was also slightly reduced due to more crop being grown in wetter districts that do well in drier years (reduced waterlogging) when yields are generally lower and vice-versa (Stephens 1997). The break point at 1982 was around the time that farmers in many areas began to sow earlier with herbicide control of weeds and better tillage techniques (Stephens 1998b). Changes to higher N inputs, crop legume rotations (Stephens 1995, 1997; Perry et al. 1998,) and the incorporation of higher-yielding semi-dwarf and rust-resistant varieties (Zwer et al. 1992; Brennan and Fox 1995) were also occurring. Figure 1.1 suggests that a steeper increase in yields in recent years, has occurred in Western Australia, and to a lesser degree in South Australia and New South Wales.

Unfortunately, the break point at 1982 also coincided with one of the most severe droughts in south-eastern Australia and this slightly amplifies the trend in the later period for States in that region. It could be considered that a linear trend through the full time series in Victoria and Queensland would be more appropriate where the yield improvements do not seem as great in recent years. At national level, yields increased at 12 kg/ha/yr prior to 1982 (Hamblin and Kyneur estimated 8 kg/ha/yr between 1950 and 1991), and 37 kg/ha/yr after 1982, a three-fold increase (Figure 1.1).
Figure 1.1. Long term average wheat yields, by State and nation, with fitted linear trends for the two intervals 1930-1981 and 1982-2000.
In this study, climate variability was removed from the yield time series in the same way as employed by Stephens (1997) and Cornish et al. (1998). The crop yield forecasting model STIN (Stephens et al. 1989; Stephens 1998) was combined into a multiple regression approach so that yields are a function of water supply and a year term linked to technology. The technology term incorporates all factors (other than seasonal rainfall) that add to change mean yields from those recorded at the beginning of the study period. Shire-level yield trends were determined for the audit period (1982 to 1996) for barley, oats and other cereals (oats, rye, triticale) and sorghum. Sequences of drought years can still reduce the inputs farmers apply and affect technological trends. Due to the number of consecutive drought years in Queensland in the early 1990s, and the requirement for as many years of data as is possible in a multiple regression approach, 1997 wheat data were extracted from the ABS sample census survey. The accuracy of this sample data was considered adequate for the major crop wheat, but for crops with small planted areas, the standard errors were considered too large by the Australian Bureau of Statistics.

Calculated trends were mapped and shown to local agronomists across the country who were asked to comment on regional differences and possible explanations. This process was a type of ‘ground-truthing’ exercise. Model-determined trends tended to match what agronomists were expecting and this added weight to explanations that they offered. Loneragan (1997) speculated that nodulated legumes combined with fertilisers (N, P, K) provided the foundation for much of the increased productivity in cropping seen in the twentieth century. To highlight the role of these factors in productivity increases, the regional pattern of N inputs and grain legume rotations were compared to regional wheat yield trends. Climate variability should adjust the increase in these factors as drier years can bring no net return from expenditure on fertiliser (even losses), and grain legumes are more sensitive to drought than cereals. Stephens (1997) demonstrated that less N fertiliser application and less lupins in rotation occurred in the drier more variable areas of the north-eastern wheatbelt of Western Australia where wheat yield trends were low. Since climate variability is translated into an agronomic performance indicator through yield variability, wheat yield variability was related at a national scale to:

(i) the rates of N application determined from the NLWRA Nutrient Balance in Regional Farming Systems and Soil Nutrient Status project (Reuter, personal communication, NLWRA 2001); and

(ii) the increase in the proportion of cropping land planted to non-cereals determined from the NLWRA project on Spatial and Temporal trends in Land Use change, Productivity and Diversification (Walcott, personal communication).

Many Australian farmers, particularly in the south, use the French and Schultz (1984a) determination of potential yield to work out their water use efficiency (WUE). This assessment of production efficiency for a given rainfall has never been calculated at a national level, so in this analysis the WUE (relative production efficiency) was determined by the ratio of actual to potential yields. Maps of this ratio across the main cropping belts formed the basis of a regional and national assessment of relative production efficiency from rainfall.
2. METHODOLOGY

The methodology for this project involved the Western Australian Department of Agriculture's automated crop yield forecasting system calculating a moisture stress index and soil moisture for each year of the analysis. Various analytical methods were then used to calculate measures of water use efficiency and trends in productivity.

2.1 Automated yield forecasting system

The yield forecasting system used in the analysis is illustrated in Figure 2.1 (Hammer et al. 1996b; Stephens 1997). This system contains a crop-yield model STIN (Stephens 1995; 1998), which uses rainfall, yield and soil data to calculate soil moisture and a moisture stress index. For each shire (SLA) in the Australian cereal cropping zone, historical Australian Bureau of Statistics (ABS) census yields were obtained. For each of these shires, STIN model parameters were determined (Stephens 1997). These included the soil water-holding capacity (WHC), a sowing date adjustment factor (for regions that plant early/late), a waterlogging sensitivity, an ending date when rainfall stops contributing to crop yield, and a total seasonal water requirement for a non-stressed crop. Each shire also had a representative rainfall and climate station selected which was typically in the centre of the cropping region in the shire. This system was used to calculate a stress index (SI) for each year of the audit analysis period.

The time series of SI was further combined with a time series of ABS shire yields in a multiple regression equation to calculate the technological trend in yields. Soil moisture at sowing and growing season rainfall were used in a calculation of potential yields and water use (production) efficiency. Results were mapped in a Geographic Information System (GIS). Only those shires, or part shires, that were within the grainbelt boundary were actually mapped. For eastern Australia, the grainbelt boundary was the same as that defined by Hamblin and Kyneur (1993), whereas for Western Australia, the clearing line on the eastern side of the wheatbelt was used in conjunction with the coastline and western boundary of western shires.

2.1.1 Data used

The data used in this analysis were:

1. Bureau of Meteorology daily rainfall for representative rainfall stations which had missing data filled with the Queensland Department of Natural Resources (QDRN) patched point dataset (Jeffrey et al. 2001).

2. Shire crop area and production data from the Australian Bureau of Statistics (ABS) between 1982/83 to 1996/97. For shires with changes in their boundaries, retrofitted data based on the 1996/97 SLA boundary were provided by the NLWRA. Shire-level wheat yield data were also extracted from the sample ABS census survey data for 1996/97.

3. Average climate data from the AUSTCLIM dataset (Nix 1981) gave required average weekly solar radiation, maximum temperatures and minimum temperatures.

4. Soils data - initial model soil parameters came with the CERES-Wheat model; other values have been derived from various papers and from other researchers. Representative soil profiles were devised for Western Australia (duplex soil with a light textured surface), South Australia (medium textured soil) and other States (heavy textured soil). All profiles had a shallow surface layer (10-15 cm) and a deeper subsurface layer. Individual shires within each State were then assigned a waterholding capacity (see section 2.1.2). The coarse nature of soil data used at a shire-level is a limitation to the accuracy of this approach.

Figure 2.1 The Department of Agriculture's automated yield forecasting system showing the flow of data between a yield forecasting model (STIN) and connected data sources and outputs.
2.1.2 Crop yield model (STIN)

The crop yield model STIN (Stephens 1998) is a refinement of that of Stephens et al. (1989), which combined the widely used FAO (Food and Agriculture Organisation) crop monitoring method (Frere and Popov 1979) with the CERES-Wheat fallow evaporation subroutine (Ritchie and Otter 1985). Instead of having a fixed, or manually determined sowing date, Stephens (1995) determined midpoints of shire wheat sowing based on rainfall amounts from a national sowing date survey (Stephens and Lyons 1998b). STIN uses the CERES evaporation model to calculate Plant Available Water (PAW) that accumulates from 1 October (in the previous year) until sowing. Then, a stress index (SI) is calculated from a potential soil water balance that runs through to the ‘ending date’ when rainfall stops contributing to final yield (Stephens 1995). The potential water balance assumes that rainfall (R) is added to the existing soil water supply and that a crop water requirement (WR) is removed at a non-limiting rate (total WR for non-stressed crop through the growing season is WRT). As such, the actual PAW at sowing is converted to potential soil water (PSW) and is calculated weekly (i) by:

$$PSW_i = PSW_{i-1} + (R - WR)$$

Usually a negative potential soil water supply is calculated, in which case an accumulative stress index (SI), which starts at 100, is reduced by the percentage of WRT not met. This index is also reduced if the water-holding capacity (or maximum PAW) of the soil is exceeded by surplus rain and waterlogging occurs. If a surplus or deficit is represented as SD then:

$$SI_t = SI_{t-1} - \frac{SD}{WRT}$$

The ‘ending date’ or average date on which rainfall stops contributing to yield occurs just after soft dough in the grainfilling stage and was determined by optimising STIN on various maturity dates (at weekly intervals). This date was compared to maturity dates calculated from a sum of degree days (base 5°C) after Walker (1989) and confirmed with the dates suggested by various district agronomists. Given the importance of the maximum PAW value in the STIN model, the stress index model was optimised for PAW in relation to final yields. Where this process gave an unrealistic value, values were chosen on the basis of the dominant soil types shown in the Soil Atlas of Australia (Northcote et al. 1975).

2.2 Analytical methods

2.2.1 Temporal yield trends

The STIN model was calibrated on shire yields from the audit period (1982/83-1997/98) and utilises a multiple regression approach to incorporate the technological increase in yields through time. Assuming a linear increase in yields with time, model predicted yields (Y) are calculated by:

$$Y = b_0 + b_1*SI + b_2*year$$

where SI is the STIN stress index and $b_0$, $b_1$, and $b_2$ are the population regression coefficients estimated by the method of least squares. The technological increase in yields in kg/ha/yr was taken as the regression coefficient $b_2$ from equation 3. These values were mapped to highlight the spatial pattern in yield trends.

By using this approach, the climate variability (variability in water supply) is removed via the stress index, leaving edaphic and technological factors contributing to the trend term ($b_2$). In interpreting these maps it is important to recognise that $b_2$ incorporates all other factors that contribute to an increase or decrease in yields. These other factors may include positive things such as:
better technology or management - fertiliser, N-fixation by legumes, improved rotations, control of root diseases, better varieties, earlier sowing, management of weeds/insects/disease through herbicides/insecticides/ fungicides, better tillage techniques, e.g. minimum tillage;

- improvement in soil properties in time - lime application, clay application to sandy soils, soil drainage (drains/raised beds);

- more favorable climate - fewer frosts, CO₂ enrichment, less storm damage, less conducive conditions for plant disease.

Negative factors that also contribute to the trend term (b₂) include:

- technological problems - herbicide resistance, more root disease with less tillage;

- decline in soil properties/degradation - nutrient and carbon loss, salinity, soil acidity, soil sodicity, soil compaction, surface ponding, wind/water erosion, water repellency; and

- less favorable trends in climate - high temperatures, higher evaporative demand, storm damage and more disease favourable sequences.

In addition, an interaction between climate and technology can occur in a series of good or poor years as these can influence the farmer’s use of technology, e.g. N application, early sowing, grain and pasture legumes. Limited farmer cashflows can restrict the farmer’s ability to purchase inputs needed to produce higher yields.

Given the number of factors contributing to trends, it is inappropriate to try to determine the contribution of each factor. However, it is informative to look at environmental constraints in different regions and compare these to regional patterns in yield trends. It is also useful if these regional yield trends are ‘ground-truthed’ with district trends noticed by observers in different regions. Regional agronomists in subregions of the wheatbelt were contacted to see if regional yield trends related to rates of technological adoption, management, soil constraints, or climatic factors. If the regional pattern of yield trends matches the regional pattern of adoption of a certain management practice, then this could be indicative of the importance of that practice. It is also useful to look at the factors that contribute to N supply as this is generally recognised to be the second major limitation behind water supply to achieving potential yields.

The percentage change in wheat yields over the audit period was also calculated using the trend term (b₂), where the increase in yields over the 15 years (1982-97) was divided by the five-year mean yields recorded at the beginning of the audit period (1982-86):

\[ YCH = \frac{(b₂ \times 15)}{Y_{ave}} \]

where:

- YCH = percentage yield change
- b₂ = yield trend in kg/ha/yr
- Y_{ave} = average shire yield (1982-86).

### 2.2.2 Water use (production) efficiency

Water use efficiency is related to the amount of grain produced per millimetre of total water used in the crop growing period. To assess water use (or production) efficiency of shire yields, actual shire yields were divided by potential shire yields (Y_{pot}) defined by French and Schultz (1984a). However, instead of using a fixed 110 mm of rainfall as soil evaporation, as was used by French and Schultz (1984a), we assumed that a third of growing season rainfall was lost to soil evaporation. This assumption prevents the actual yield exceeding the potential yield in drought conditions (Tennant, personal communication). Therefore,
$\text{WUE} = \frac{Y_a}{Y_p}$  

$Y_p = W \times WUE_p$ 

$= (GSR + SM - E) \times WUE_p$ 

$= (GSR + SM - (0.33 \times GSR) \times WUE_p$  

where:

- WUE = water use efficiency
- $Y_a$ = actual yield
- $Y_p$ = potential yield
- $WUE_p$ = potential water use efficiency (20 kg/ha/mm)
- W = water used
- GSR = growing season rainfall (between sowing and rainfall 'ending date' in STIN)
- SM = soil moisture at sowing determined by STIN
- E = soil water losses to evaporation.

French and Schultz (1984a) noted that evaporation can be as low as 14-18 per cent of water use in northern cropping areas in Queensland, which means this approach would underestimate potential yields in these regions. However, in the calculation of soil moisture at sowing, a fallow evaporation model was used which assumed there was no plant growth leading up to sowing. This would tend to lead to an overestimation of potential yields where summer pastures, weeds or another crop was grown, which is much more likely in the summer rainfall dominant regions in northern cropping areas. It was therefore assumed in northern regions that rainfall losses from summer plant growth would balance out less evaporation in winter and that a uniform approach could be used across the country for comparison. The same approach was used for all crops in this study. It is worth pointing out that by removing evaporation losses from the water supply we are actually calculating ‘transpiration efficiency’. However, for a wider readership we have adopted the more commonly used WUE.

2.2.3 Yield variability

Crop yield variability across seasons is a major constraint on farm management, so the coefficient of variation of yields was calculated for the audit analysis period for the major crop wheat. Yields were first de-trended to remove the confounding effect of technological increases which add to normal yield variation. Actual ABS shire wheat yields were de-trended using a multiple regression equation and the yield trend calculated in Equation (3).

$$Y_{det} = Y_{abs} + b_2 \times (1997\text{-year})$$  

where $Y_{det}$ is the de-trended yield assuming 1997 technology, $Y_{abs}$ is the Australian Bureau of Statistics shire yield, $b_2$ is the increase in shire yields (kg/ha/yr) over the analysis period and year is the year that the crop was grown. The coefficient of variation of these detrended yields was calculated by:

$$CV = \frac{sd}{\bar{x}}$$  

where:

- CV = coefficient of variation
- sd = standard deviation of de-trended yields
- $\bar{x}$ = mean of de-trended yields.
3. RESULTS

The results from this analysis are plotted in the appendices. Since wheat is the major crop grown in Australia, and a major source of farm income, factors which affect wheat productivity are of great importance to long-term farm profitability (Hamblin and Kyneur 1993). Therefore, the majority of the discussion and analysis centres on trends in this crop (section 3.1). Trends in wheat yields (Appendix 1) and percentage increases in wheat yield (Appendix 2) are compared to a number of other factors mapped in Appendices 3-12 (section 3.1.1). In section 3.1.2, a regression analysis is made between yield trends in Appendix 1 with factors plotted in appendices:

- 3 - average shire wheat yields,
- 4 - wheat yield variability,
- 7 - change in crop diversity, and
- 8 - total N inputs.

The role that climate variability has in adjusting N inputs and rotation changes is also made. This is supported by a State by State summary of regional trends in yield and farming practices (sections 3.1.3 to 3.1.7). Discussions with regional agronomists were most helpful in interpreting these regional patterns. Trends in the other main winter cereals are discussed in section 3.2 and are mapped in Appendices 13 (barley) and 14 (oats and other cereals), while trends for summer sorghum are mapped in Appendix 15. Average water use efficiencies in shire yields follow in sections 3.3 and are mapped in Appendices 16 (wheat), 17 (barley), 18 (oats and other cereals) and 19 (sorghum).

3.1 Trends in wheat yields

3.1.1 National patterns - overview

Trends in shire wheat yields show considerable variation across the wheatbelt (Appendix 1). Both the range in trends and the general magnitude of trends were much higher than those mapped at a shire-level by Hamblin and Kyneur (1993). Highest wheat yield trends (> 60 kg/ha/yr) occurred in south-eastern and north-eastern New South Wales, north-western and south-western Western Australia, wetter districts in South Australia and the south-eastern edge of the Darling Downs in Queensland. Lower wheat yield trends tended to occur in drier regions, but this tendency was not as strong as that found in the yield trend map of Hamblin and Kyneur (1993). Highest percentage increases in wheat yields (> 75 per cent) occurred across Western Australia, south-eastern and northern New South Wales and in south-eastern South Australia (Appendix 2). A comparison between Appendix 1 and the following appendices highlights the following generalisations.

Firstly, there was a weak relationship between yield trends (Appendix 1) and average yields (Appendix 3) with higher trends generally occurring where average yields were higher. Exceptions to this are lower trends for higher yields in southern Victoria and the northern Darling Downs, and higher trends for lower yields over much of Western Australia and northern New South Wales. Yield trends in Appendix 1 are more closely related to yield variability (Appendix 4) and rainfall reliability between June and September (Appendix 5). Very low to negative trends were found where yield variability was high and unreliable winter/spring rainfall occurs. The low yield trends in the moderately stable climate of southern once again defy the national trend.

Trends in wheat yields also matched crop diversity (proportion of non-cereals in winter crop rotation) (Appendix 6). Notable exceptions were very low trends which coincided with the large amounts of cash legume crops (chickpeas, peas and lentils) in the Victorian Wimmera, large amounts of sunflower, chickpeas and mung beans in far northern Queensland, and higher trends in northern New South Wales, where a low proportion of non-cereals are grown.
in rotation. These three regions also differ from the ‘norm’ when wheat yield trends are compared to changes in crop diversity (i.e. changes in proportion of non-cereals in winter rotation, Appendix 7), which seems to relate to trends in other regions. Regional wheat yield trends also seem to be strongly related to total N inputs from all sources (fertilisers, pastures, grain legumes) (Appendix 8), and the N balance (Appendix 9) determined in the NLWRA. Lower N inputs and negative N balances generally occurred across most of Victoria and Queensland where yield trends were lower. Higher N inputs and positive to neutral N balances occur widely over the higher yield trending areas in Western Australia, South Australia and New South Wales. The fact that this relationship applies across the whole cropping belt supports the assumption by Hamblin and Kyneur (1993) and Cornish et al. (1998) that N is a major driver of productivity increases in Australia.

Hamblin and Kyneur (1993) also noted that low or negative yield trends occurred where high cropping intensities had affected pasture quality, soil organic matter and N levels. However, the intensity of winter cropping in 1997 (Appendix 10) reveals that high cropping intensities (> 40 per cent) occurred where some of the most positive wheat yield trends had occurred in Western Australia, South Australia and New South Wales (Appendix 1). Lower trends in the Victorian Wimmera coincided with greater than 50 per cent cropping intensity. The overall change in cropping intensity through the audit period actually increased in the more Mediterranean climates, and decreased in the uniform to more summer-dominant rainfall climates (Appendix 11). Much of this change in intensity is related to the increase (or decrease) of non-cereals in rotation (Appendix 7). A 10-20 per cent increase in crop intensity in western and northern districts of Victoria coincided with a marked reduction in long fallows and a 5-35 per cent increase in pulses and oilseeds in rotation (Appendix 7).

Lack of financial resources to address declining soil fertility, was also proposed as a limiting factor to productivity increases (Hamblin and Kyneur 1993). Based on Australian Bureau of Agricultural and Resource Economics (ABARE) farm surveys, Appendix 12 highlights that five-year average farm business profit at the end of the audit period was positively related to wheat yield trends mapped in Appendix 1. Higher farm profits go together with productivity increases, lower yield variability (Appendix 4) and high cropping intensities (Appendix 10). Better incomes in the Victorian Wimmera and northern Queensland, where yield trends are low, probably related to growing legume ‘cash crops’. Very low farm profits occurred in much of the cropping area of Queensland and the regions of high yield variability in drier areas of South Australia and central New South Wales. Lower profits on the wetter edges of the wheatbelt, where more sheep have traditionally been grazed, directly related to the low wool prices received through 1992-96. Alternatively, Appendix 12 suggests that profitability has enabled farmers to increase inputs, and has encouraged a change in attitude to higher input agriculture.

To differentiate more clearly the role of different factors contributing to yield changes, a more detailed analysis is necessary and this follows.

3.1.2 National patterns - analysis

Wheat yield trends vary considerably across the country and it is important to first recognise the considerable environmental variations that occur. Generally, as one moves anti-clockwise around the country from Western Australia to Queensland, there is a gradual change from a winter-dominant, to a summer-dominant rainfall distribution (Gentilli 1971), and from shallow lighter textured soils to deeper heavy soils (Nix 1975). This is associated with a change from a reasonably stable climate with low yield variability to a more variable climate with high yield variability (Stephens and Lyons 1998a). In the south-west of Western Australia the lower yield variability is also caused by soils that cannot store much moisture, a plateau of yields with higher rainfall, and lower yields in wet winters (Hoyle and Anderson 1993; Stephens 1995).

This gradual change in crop environment is graphically illustrated in Figure 3.1 for the
Figure 3.1. The coefficient of variation in de-trended shire wheat yields plotted as a function of mean yields. South-eastern Australia includes South Australia, Victoria and New South Wales. Logarithmic curve of best fit in each case.

Figure 3.2. Trend in shire wheat yields versus the variability in de-trended shire yields (1982-97). South-eastern Australia includes South Australia, Victoria and New South Wales. Logarithmic curves of best fit in each case.
approximate Grains Research and Development Corporation (GRDC) zones. (Note: northern NSW included in south-east Australia, whereas it is normally in northern zone.) When mean yields (Appendix 3) are compared to the coefficient of variation in yields (Appendix 4), the highest yield variability is found in arid low yielding areas and lower variability in higher yielding areas. However, between regions, there is a dramatic increase in yield variability (for a given mean yield) as one progresses from Western Australia around to Queensland. The relationship between mean yields and variability becomes stronger as one also progresses towards the north-eastern regions, with 25 per cent (Western Australia), 31 per cent (south-eastern Australia) and 72 per cent (Queensland) of the variance in yield variability explained by mean yield levels. The slope of the relationships indicates that yield variability increases more dramatically as yields decline in eastern and northern regions of the country.

When the trend in wheat yields (Appendix 1) is compared to yield variability in de-trended yields through the audit period (Appendix 4), higher yield trends are generally found in shires with lower yield variability (Figure 3.2). Negligible to negative trends occur once the coefficient of variation (CV) increases above 0.5, while almost all shires had a trend > 40 kg/ha/yr if the coefficient of variation in yields was < 0.15. The relationship between yield trend and variability also became stronger in north-eastern Australia, with the coefficient of determination ($r^2$) increasing from 0.27 in Western Australia, 0.43 in south-eastern Australia, to 0.47 in Queensland.

Since Western Australian yields have increased from a lower base yield than in other States (approximately 1-1.5 t/ha at beginning of 1980s), the largest percentage increase in yields occurred for many of its shires over the audit period (Appendix 2). When the percentage increase is compared to the variability of yields, a slightly stronger relationship is found at a national level (Figure 3.3). Most shires with a CV in yields less than 0.3 had at least a 40 per cent increase in yields, while those with a CV in yields greater than 0.3 had less than a 40 per cent increase.

The relationship between wheat yields trends and mean yields (Figure 3.4) also highlights the lower trends in the more arid lower-yielding regions. Where lower yields occur, trends in yield were generally lower, although a large amount of scatter occurs when yields were < 1.6 t/ha. Four shires with high mean yields (> 2 t/ha) had very low to negligible trends. These included the three shires in the Wimmera in Victoria (Hindmarsh, Yarriambiack South and Horsham RC Central) and the small producing shire of Cabonne South part B in New South Wales. Only 22 percent of the variance in yield trends can be explained by mean yields in Western Australia compared to 38-40 percent in eastern Australia. Low yielding shires (< 1.75 t/ha) in Western Australia outperformed those in other States as there is a divergence in yield trends between regions at the lower range.

The important role of yield variability in influencing yield trends appears to relate to the way in which climate variability has affected:

1. the amount of N inputs applied to crops; and
2. the amount of grain legumes and oilseeds grown in rotation.

When N inputs from fertilisers and legumes at a shire level (NLWRA 2001) are compared to yield variability, a number of features become clear (Figure 3.5). In the low yield variability environment of Western Australia, much more N is applied to wheat crops through fertilisers, grain legumes and ley pastures than in Queensland (Figure 3.5a). The lowest N application in Western Australia mostly occurred in the more variable yielding shires, whereas the highest application rates always occurred in the more stable regions of Queensland. A lot of scatter in the relationship occurred in the more stable regions of each State. In south-eastern Australia there was more scatter in the relationship, but clear differences occurred between States (Figure 3.5b). In New South Wales the large range in N application highlights the range in cropping from irrigation to rain-fed agriculture, and a range of other crops grown. Highest
application rates occurred in the irrigation areas where yield variability was low. South Australian N application rates more closely correlated with variability, with N rates nearly always exceeding 25 kg/ha if the CV in yields was less than 0.2, or less than 25 kg/ha if the CV in yields was greater than 0.35. Yield variability in Victoria was not related to the very low N fertiliser application rates found in the audit (NLWRA 2001).

The role of climate variability in adjusting the amount of crop diversity is illustrated in Figure 3.6. Here, yield variability (Appendix 4) is compared to the change in percentage of cropping that is non-cereal (Appendix 7). In the three higher trending States (Figure 3.6a) there was generally less of a change to non-cereals in the more variable yielding environments (and vice versa). Pulses and oilseeds are poorly adapted to semi-arid conditions and the profitability is very poor in dry conditions (Angus et al. 1991). If the CV in wheat yields exceeded 0.35, negligible changes in crop diversity generally occurred, whereas a 10-25 per cent increase in non-cereal crops generally occurred if the CV was less than 0.2. Larger changes to the general rule occurred in southern central New South Wales, where canola has done well and the positive effect of ‘break’ crops on wheat yields was significant. Lowest rate of adoption of non-cereals was in the fertile soils of north-eastern New South Wales where N inputs had increased and sorghum provides the break crop effect (Hayman, personal communication). Half the variance in the trend in non-cereal adoption in South Australia can be explained by the yield variability in South Australia. This suggests that the reliability of rainfall may be playing an important role in driving the crop rotations in this State.

In the two States with lowest yield trends there is a contrasting story with crop diversity (Figure 3.6b). In all shires in Queensland there has been a negligible increase, to marked decline, in the proportion of non-cereals in rotation. Very low non-cereal yields were recorded through the drought years of the 1990s and the high climate variability makes it difficult for rotational planning (Cornish et al. 1998). Reduced adoption of grain legumes in southern Queensland appears to also be limited by the lack of profitability of these crops on the large areas of vertisol soils (Hamblin and Kyneur 1993). Chickpeas are the main grain legume (Freebairn, personal communication) because of profitability (Beech and Leach 1989). In Victoria, there was been a different trend as the highest increase in non-cereals occurred in the variable mixed farming areas in the north-east (Figure 3.7b). Earlier adoption of grain legumes in the Wimmera, and the move away from sheep into small cropping enterprises in the north-east (Belford, personal communication), are the main factors driving this inverse relationship. Overall, it can be concluded that pulses and oilseeds have been more widely adopted in more stable yield environments, with yield variability most influencing crop diversity in South Australia and Queensland (negligible adoption).

With yield variability influencing N inputs (Figure 3.5) and changes in rotation (Figure 3.6), the obvious next question is: Are N inputs or rotation changes important in ‘explaining’ the yield trends?, i.e. the relationship between yield variability and trends (Figures 3.3 and 3.4). Unfortunately, data collected in the NLWRA only had fertiliser application data at a shire-level from 1992-1996, so the trend in fertiliser application through the audit period could not be related to yield trends. However, Greenwood (1983) found that 83 per cent of the variance in mean crop yields in populous countries is explained by the amount of fertiliser applied. So, the mean rate of total N applied to crops (from all sources including legumes) between 1992 and 1996, was regressed with wheat yield trends from Appendix 1 (Figure 3.7). As the time frame for N application rate does not relate to the time frame of the trend, and since not all N was applied to wheat, a lot of scatter is found in the relationships. However, the general increase in yield trends with higher N application for four of the States supports the important role nutrients play in productivity increases. There was little relationship between N inputs and yield trends in Victoria as the highest trends occurred in small producing shires where low N inputs occurred. It appears that other management factors related to a greater emphasis on cropping (better weed control, earlier sowing, fungicides, raised-bed farming) are driving trends in these areas. Nutrient data obtained in the audit should continue to be collected so that trends in application can be used to better define these important relationships.
Figure 3.3. Percentage increase in shire wheat yields (1982-97) compared to the variability in de-trended shire yields (1982-97). South-eastern Australia includes South Australia, Victoria and New South Wales. Logarithmic line of best fit in each case.

Figure 3.4. Trend in shire wheat yields (1982-97) compared to the mean wheat yields through the 1982-1997 period. Western Australia top line, Queensland middle line, south-eastern Australia bottom line. Linear line of best fit in each case.
Figure 3.5. Mean rate of nitrogen inputs at a shire level from all sources (1992-96) compared to the variability in de-trended shire wheat yields (1982-97). A logarithmic line of best fit is applied in each case, except a linear fit in Victoria \((r^2 = 0.52 \text{ New South Wales}, r^2 = 0.34 \text{ Queensland}, r^2 = 0.30 \text{ South Australia}, r^2 = 0.23 \text{ Western Australia}, r^2 = 0.03 \text{ Victoria})\).
Figure 3.6. Change in non-cereal percentage (1983-1996) compared to the variability in de-trended shire yields (1982-97). Logarithmic lines of best fit in: (a) South Australia \( r^2 = 0.50 \), Western Australia \( r^2 = 0.21 \), New South Wales \( r^2 = 0.17 \); and linear lines of best fit in: (b) Victoria \( r^2 = 0.12 \), Queensland \( r^2 = 0 \).
Figure 3.7. Trend in shire wheat yields (1982-97) compared to the mean rate of total nitrogen applied to cropping between 1992 and 1996. Linear line of best fit in each case ($r^2 = 0.36$ South Australia, $r^2 = 0.31$ Western Australia, $r^2 = 0.26$ Queensland, $r^2 = 0.20$ New South Wales, $r^2 = 0.01$ Victoria).
Figure 3.8. Shire wheat yield trends (1982-97) versus the change in non-cereal percentage (1983-1996).

Linear lines of best fit in: (a) South Australia (steep slope to line) $r^2 = 0.46$, Western Australia (small slope) $r^2 = 0.03$, New South Wales (top line) $r^2 = 0.15$; and linear lines of best fit in: (b) Victoria $r^2 = 0.08$, Queensland $r^2 = 0$. 
For much of the Australian wheatbelt higher wheat yield trends (> 40 kg/ha/yr) occurred when the change in non-cereal percentage in rotation exceeded a 15 per cent increase (Figure 3.8). However, the overall relationships between these two variables varied from State to State. The strongest relationship ($r^2 = 0.46$) occurred in South Australia (Figure 3.8a) where a whole range of management changes coincided with a large increase in crop diversity and higher trends in the more reliable shires. In New South Wales there was a north-south gradient in uptake of non-cereals (Appendix 7), apparently related to the reliability of winter/spring rainfall and the suitability of soils. Wheat yield trends in southern New South Wales matched the increase in diversity (especially uptake of canola), but higher trends in the north were associated with the benefits of a summer sorghum break crop (not measured in winter non-cereal percentage) and higher N inputs (Hayman and Alton 1999). In Western Australia, there was no real relationship with trends and an increase in crop diversity, suggesting that this was just one of a number of array of variables that had contributed to positive yield trends. In Victoria and Queensland there were weak negative relationships between changes in non-cereals in rotation and wheat yields (Figure 3.8b). Contrasting decreases (Queensland) and increases (Victoria) occur and match the overall low (Queensland) and high (Victoria) crop diversity (Appendix 6). The ‘inverse’ result in Victoria was dominated by some high yield trends in very small producing shires, where farmers had concentrated more on cropping (than livestock), but who didn’t have the land area for pulses and oilseeds. Also, in the Victorian Wimmera, low wheat yield trends coincided with a dramatic increase in ‘high value’ cash legume crops. Wheat yields suffered as greater attention was given to non-cereal yields, whilst limited soil N re-cycling from the legumes did not assist the following wheat crops as much as would normally be expected (Belford, personal communication).

On the whole, regional yield trends cannot be explained with one factor alone. Although it would appear that the combination of better nutrient and rotation management are important factors behind the large step up in yield trends found in Western Australia, South Australia and New South Wales (Figure 1.1). Lower continuing trends in the other States have coincided with less N application from fertilisers, and low N fixation from small areas of pulses in Queensland, and low N fixation from large areas of ‘cash’ legume crops in Victoria. Certainly, other factors are important at a regional scale and these will now be examined in more detail on a State by State basis.

### 3.1.3. Western Australia

Most of the Western Australian wheatbelt had a substantial 45-75 kg/ha/yr increase in wheat yields over the audit period (Appendix 1). Three shires in the far north-west (Mingenew, Irwin and Greenough) and Plantagenet, in the far south, had increases greater than 75 kg/ha/yr. In contrast, three northeastern shires (Nungarin, Westonia and Yilgarn) had increases less than 30 kg/ha/yr. Compared to the 1-27 kg/ha/yr increase in wheat yields found by Hamblin and Kyneur (1993) between 1950 and 1991, these later yield increases support the assumption that there has been a step increase in yield trends, as plotted in Figure 1.1. With yields coming off a low 1-1.5 t/ha base in the early 1980s, the percentage increases in yield were generally the highest in the country and were greater than 90 percent in north-west shires (Appendix 2).

Compared to other States, yields increased more uniformly across regions and this probably relates to widespread adoption of a high yielding agronomy package based on new varieties and better management. From a series of trials, Anderson (2002) estimated that 32 per cent of recent yield gains have come from improved wheat cultivars and 68 per cent from better agronomic practices. New semi-dwarf varieties outperform older taller varieties with high inputs and early sowing (Anderson and Smith 1990; Anderson 1992). Consequently, a high yield package was promoted with low-cost management measures (soil type selection, grass weed control, legume rotation, semi-dwarf varieties, early sowing) combined with increases in N, seeding rate and fungicides, i.e. generally equates to a ‘high-input, high-output’ farming system. These changes were encouraged by better seasons (late 1980s-1990s), and surveys
showing higher farm operating profits linked to farmers who produced higher crop yields (Australian Farm Journal 2000).

In terms of plant breeding and varietal changes, Western Australia had the largest uptake of new semi-dwarf based varieties through the audit period. Brennan and Fox (1995) and Brennan (personal communication) estimated that the proportion of semi-dwarf varieties increased from 15 to 90 per cent of sown wheat through the audit period. Such a rapid change was probably assisted by a local breeding and agronomic program that successfully adapted semi-dwarf varieties to local Mediterranean conditions (Perry and D’Antuono 1989; Anderson and Smith 1990; Siddique et al. 1990). The proportion of Western Australian-bred wheat varieties planted increased from 10 to 43 per cent between 1982 and 1997, and subsequently to 84 per cent in 2001 (Brennan, Loughman personal communication). Yield advantages of the semi-dwarf cultivars, which were not evident using traditional agronomic practices of the 1970s and early 1980s, were shown to be considerable with early sowing and high inputs (Anderson and Smith 1990). The genetic improvement of locally bred varieties that added to these yield increases were mainly achieved through substantial increases in grain number per square metre associated with an improvement in harvest index (Perry and D’Antuono 1989). Local cultivars had an improved water use efficiency which was associated with faster leaf area development, earlier flowering, improved light interception from better canopy structure, and reduced early season evaporation losses (Siddique et al. 1990). The proportion of Western Australian-bred wheat varieties planted increased from 10 to 43 per cent between 1982 and 1997, and subsequently to 84 per cent in 2001 (Brennan, Loughman personal communication). Yield advantages of the semi-dwarf cultivars, which were not evident using traditional agronomic practices of the 1970s and early 1980s, were shown to be considerable with early sowing and high inputs (Anderson and Smith 1990). The genetic improvement of locally bred varieties that added to these yield increases were mainly achieved through substantial increases in grain number per square metre associated with an improvement in harvest index (Perry and D’Antuono 1989). Local cultivars had an improved water use efficiency which was associated with faster leaf area development, earlier flowering, improved light interception from better canopy structure, and reduced early season evaporation losses (Siddique et al. 1990). Plant breeding has also incorporated multiple rust resistant genes (Zwer et al. 1992) and several varieties have been released in Western Australia with improved yield responses to the commonly occurring leaf spot diseases caused by \textit{Phaeosphaeria nodorum}, \textit{Mycosphaerella graminicola}, and \textit{Pyrenophora tritici-repentis} (Loughman et al. 1999).

A number of improvements in agronomy occurred during the audit period. A significant 10-30 per cent increase in the proportion of crop area planted to grain legumes and oilseeds occurred (Appendix 7), benefitting wheat yields in a number of ways. Most importantly, grain legumes stimulate wheat yields through N-fixation in the soils, but also through increased root depth and post-anthesis water uptake in the following wheat crop (Asseng et al. 1998). Other system benefits from grain legumes include the opportunity for weed control, a break for fungal disease, and improved soil structure and nutrient cycling (Perry et al. 1998). On a duplex soil in Western Australia, 66 per cent of the variance in increased wheat yields in a rotation experiment was attributed to residual N from previous grain legume crops (Asseng et al. 1998). Lupin area in this State increased from 0.2 m ha to 1.1 m ha over the period 1982 to mid-1990s and became prominent on light sandier soils (Perry et al. 1998). Given that very high amounts of residual N (65-96 kg/ha/yr) are left in the soil following lupins (Unkovich et al. 1994; Asseng et al. 1998; Evans et al. 2001), this can have a significant impact on following cereal production. The widely used wheat/lupin rotation can result in a 40-135 per cent increase in wheat yields over those obtained from continuous wheat cropping (Rowland et al. 1988; Asseng et al. 1998; Gregory 1998). The net effect of grain legume N-fixation on the soil N balance for a combination of legumes (lupin, pea and chickpea) was twice that for south-eastern Australia (Evans et al. 2001). Larger yield responses in Western Australia are mainly due to the inherent infertility of Western Australian soils (Unkovich, personal communication). Later in the 1990s, the release of triazine and blackleg resistant canola enabled this break crop to be more widely used in Western Australia with 0.25 m ha being planted in 1997. Canola increased subsequent wheat yields 22-102 per cent through a cleansing effect on soil of root diseases (Gregory 1998), which in turn assists crop root extension and overall nutrient and water extraction. The weak relationship between yield trends in Western Australia and the change in non-cereal percentage (Figure 3.8a) was affected by two factors. Lupins were incorporated into rotation earlier in the 1980s in the north, whilst less prevalent root diseases (Brennan and Murray 1998) mean that the benefits of canola as a break crop are not generally as great as they are in eastern Australia (Carmody, personal communication).
Higher application rates of N fertiliser and better legume pastures further increased N supplies to wheat. Many good seasons and simple tools that estimated soil N needs (Bowden and Burgess 1993) encouraged N application on crops to increase from 1-40 kg/ha/yr to 10-80 kg/ha/yr between 1992/93 and 1996/97 (NLWRA 2001). Soil N also benefited from the largest Statewide sowing of new legume pastures (ABARE 1999). In addition, subsurface acidity became recognised as a major limitation to cereal production across significant areas of the wheatbelt and an active ‘Time to Lime’ program was promoted by the Western Australian Department of Agriculture. From 1994/95 to 1998/99, the application of agricultural lime increased from 140,000 ha per annum to 586,184 ha per annum, leaving 2.1 million ha of acid soil being treated (Miller 2001). Western Australian farmers also turned a negative potassium balance to neutral or slightly positive through the 1990s (NLWRA 2001).

Stephens and Lyons (1998b) found a two to three week switch to earlier sowing through the 1980s that coincided with the increased planting of long season varieties (Stephens 1995). Earlier sowing promotes higher yields as more crop growth occurs in a cooler environment with lower average evaporative demand (French and Schultz 1984a). It also means crops can better handle waterlogging in mid-winter in wetter districts (Belford et al. 1990). Grain yield losses for delayed planting after an ‘optimal planting date’ average about 25 kg/ha/day in Western Australia (Anderson, personal communication). A switch to earlier sowing also coincided with one of the largest Statewide trends to minimum tillage practices and increased chemical spraying of weeds. Near the end of the audit period, Ha and Chapman (2000) and Wallwork (2001) found that 41-50 per cent of Western Australian farmers were using direct drilling or zero tillage (one pass with narrow points or discs), the highest adoption rate in the country. Conservation tillage has the tendency to improve yields through better moisture retention, reduced erosion, and better soil properties, e.g. higher carbon and nutrient levels (Wallwork 2001). In association, herbicide use increased three-fold increase in area in Western Australia from 1982 to 1994 (Stephens 1995), and a further 50 per cent increase is apparent from 1994 to 1999 (Australian Farm Journal 2000). However, herbicide resistance is now a major concern and may limit further yield increases.

Regional differences in yield trends in this State have some resemblance to annual rainfall zones and regional soil properties. Generally, the lowest trends occur in the drier north-eastern shires where yield variability is higher (Appendix 4). Farmers in this region are more conservative in their inputs with the four lowest yielding shires (Appendix 3) all having very low rates of applied N (Figure 3.5a) and low adoption rates of non-cereals (Appendices 6 and 7). One of the strongest relationships between crops and soil types is the predominant cultivation of lupins on deep, coarse textured soils with acid to neutral reactions (White 1990). In the north-eastern shires there is a greater occurrence of heavy red clay loamy soils, or strongly acidic sandplain ‘Wodgil’ soils. These have not been suitable for narrow-leaf lupins and the ratio of lupin to wheat area has been low (Stephens 1997). ‘Wodgil’ soils also have low nutrient contents, often high levels of extractable aluminium in the subsoil, and are common in areas with severe brown spot and root rot disease caused by Pleiochaeta setosa (French et al. 2001). Water repellency of light soils in the Esperance and Albany shires has probably limited cereal yield trends in these southern shires (Crabtree, personal communication).

Conversely, high yield trends in north-western shires (Goomalling to Northampton) occur where there is a predominance of sandplain country (sand, sandy duplex) and high yield trends match the high proportion of lupins in rotation (Stephens 1997, Appendix 6). Farmers in north-western shires have also embraced soil acidity technology more quickly than central and south-eastern parts of the State (Clune and Gartner 2001). Highest yield trends occur where cropping has replaced grazing as the most profitable enterprise and where a swing to lupins occurred in the 1990s (e.g. Northampton, Irwin, Plantagenet and Gnowangerup). In central/southern shires there has been less than 20 per cent of wheat crop area planted to lupins, and release of grass selective herbicides (Fusilade®) probably played a greater role (Duncan, Nelson, personal communication). Herbicides for grass control can be effective in
decreasing yield losses caused by take-all disease, weed competition and insects (Anderson 2002). The benefit of good pasture legumes was highlighted by one farmer from the south central region who commented that clover and medics benefited the following wheat crops to the same or greater degree than lupins.

Finally, Western Australian growers had higher cash incomes and higher rates of return than other States (compare Appendix 12), enabling substantial investment in new capital and state-of-the-art machinery (Knopke 2000). Very large farms in this State also allow flexibility in rotations and lower capital input per hectare cropped than other areas (Knopke et al. 2000). Henderson and Kingwell (2002) found farm size has a positive relationship with allocative efficiency (profitable combinations of inputs and outputs).

### 3.1.4 South Australia

Hamblin and Kyneur (1993) found only small increases in wheat yields (< 9 kg/ha/yr) across most of South Australia between 1950 and 1991. Black (1998) found State wheat yields had increased at 1 per cent per annum, or 19 kg/ha/yr, in the 30-year period up to 1994. However, most of the increase in this later study was found in the higher rainfall areas (> 400 mm annual rainfall). Yield trends calculated in this study (Appendix 1) were generally higher, and in some cases much higher (> 75 kg/ha/yr), than those from the earlier studies. Similar to Anderson’s (2002) assessment of Western Australian yield trends, Black (1998) attributed 35 per cent of recent wheat yield increases to breeding, and 65 per cent of yield increases to farming systems research. From 1982 to 1997, the proportion of wheat planted to higher yielding semi-dwarf varieties increased from 52 to 97 per cent (Brennan and Fox 1995; Brennan, personal communication). A swing to earlier sowing (Stephens and Lyons 1998b), minimum tillage practices (Wallwork 2000), higher N inputs (NLWRA 2001) and more non-cereals in rotation (Appendix 7) has also been observed.

Of all States, South Australian wheat yield trends (Appendix 1) vary the most at a regional scale, and most closely follow patterns of annual rainfall. As was found by Black (1998), the division between higher trends (greater than 45 kg/ha/yr) and lower trends closely follows the 400 mm annual isohyet, with trends decreasing from the wet, to medium, to dry rainfall zones defined by Stephens and Lyons (1998a). The higher rainfall areas have less climate variability with the coefficient of variation in yields similar to that found in most of Western Australia (Appendix 4). Average yields are consistently greater than 2 t/ha in wetter areas and lower than the 1.5 t/ha in drier areas (Appendix 3). The fact that actual and percentage increases in yields have been higher in wetter areas through the audit period points to a greater gradient in average yields forming between wetter and drier areas.

Discussions with agronomists in South Australia (Lewis, Holloway, McDonough, Egan, personal communication) highlighted consistent reasons for the gradient in yield trends through the 1980s and 1990s. These related to a number of environmental and economic issues that differed between wetter and drier areas.

In wetter areas a better understanding of farming systems has coincided with improved management practices. These include:

1. Crop diversity increased dramatically with grain legumes and canola increasing their percentage of total crop area from 5-25 per cent (Appendix 7). Break crops such as canola dramatically reduced root diseases which are a major limitation to yields in wetter areas. These crops significantly reduced the effects on final yield from rhizoctonia, root and lesion nematode, cereal cyst nematode (CCN) and take-all.

2. In wetter areas better trace element management occurred in conjunction with changing crop rotations. Nitrogen inputs increased dramatically and enabled crops to better utilise the available water. Pastures can also supply substantial N to crops.

3. On lighter soils, farmers have turned more to minimum tillage and cultivation tends to occur more on opening rains. This has assisted in bringing sowing earlier, while
spraying weeds with chemicals before cultivation has further reduced the disease risk.

(4) Foliar plant diseases are controllable with fungicide sprays, but with a cost of $25/ha this is often only economic for crops with an average yield of 2.0 t/ha (Brennan and Murray 1998). These higher yields are generally found in wetter districts.

In drier areas, environmental and economic constraints have limited the adoption of new and better management practices. These include:

(1) Crop diversity only increased 1-5 per cent of total crop area (Appendix 7) and was restricted by the unprofitable nature of non-cereals. Canola yields were too low to cover the high cost of cultivation and losses were made in dry years. In northern regions of the Eyre Peninsula, mid-north and southern Mallee, the highly calcareous soils and sodic subsoils are unsuitable for lupins. The low and variable rainfall in these districts makes other grain legumes a high risk option, although profitable in better years, especially when the season break is early. Field peas are the most reliable crop for many of the alkaline soils, but these leave a high wind erosion potential on light soils after harvest, and are unsuited to stonier (limestone) soils due to harvest problems. The lack of break crops has meant that root diseases are now more prevalent in drier areas.

(2) Very low rates of N are applied in the drier, more variable areas and nutrient deficiencies limit yields in wetter years. In these regions the nutrient status of soils and subsoils (P, N and trace elements) tends to be lower, with lower organic carbon and biological activity. Hostile subsoil factors (e.g. boron toxicity and high sodicity) also limit root growth on many of these soils, further restricting the plants’ ability to access soil water and nutrients. Medic pastures generally do not produce enough N for following crops.

(3) Farmers in drier areas have changed less to minimum tillage, probably because of increased nematodes with no-till on the prevalent alkaline sands. The Eyre Peninsula Regional strategy (rural adjustment program) greatly promoted and facilitated the adoption of minimum tillage machinery and practices in the 1990s. The impact of these changes may not have been yet reflected in the audit data. Weeds have been more of a problem where herbicide use has been more limited.

(4) The high yield variability, lower average yields and lower crop profitability have limited the investment in new technologies and high input cropping systems. With the higher climate risk, farmers have tended to be conservative, although investments in the Eyre Peninsula and Mallee did start to take effect later in the 1990s. Black (1998) noted that in lower rainfall areas, reduced land prices assisted in the quest to remain viable by allowing farmers to increase their land size.

3.1.5 Victoria

Victorian wheat yield trends were generally low (15-45 kg/ha/yr), but overall had increased from the 4-21 kg/ha/yr generally found by Hamblin and Kyneur (1993). Yield trends ranged from decreasing yields in the Hindmarsh and Mildura (RC) - Part A shires, up to 69 kg/ha/yr at Strathbogie shire in the north-east. In all areas very low rates of bagged N were added (1-10 kg/ha/yr). High levels of boron and sodicity in the southern Mallee and Wimmera have meant that N use efficiency has been low compared to other areas, such as south-eastern NSW. In regions that grow large amounts of barley, N inputs have been kept low to prevent the protein of the barley being too high for malting, which is paid a premium. Nitrogen inputs are also kept low in the profitable grain legume phase of rotations. Most of the change to semi-dwarf varieties occurred earlier (1970s or early 1980s) (Brennan and Fox 1995), with the proportion of semi-dwarfs increasing from 65-97 per cent of total wheat plantings from 1982 to 1997 (Brennan, personal communication). A nationwide swing to early sowing was least pronounced in Victoria during the 1980s (Stephens and Lyons 1998b).

There are four major areas of production: 1) the low rainfall Mallee (north) where soils are predominately alkaline and sandy/loamy textured, 2) medium rainfall Wimmera (south
central) with large areas of fine textured alkaline soils, 3) medium rainfall north-east with acid soils, and 4) high rainfall south-west on acid soils (<3 per cent of production and not covered in this report) (Belford, personal communication).

In the Mallee, wheat yield trends were low (0-30 kg/ha/year). Due to the lower reliability of winter/spring rainfall than southern areas (Appendix 5), the farming system continued to rely on wheat/pasture/fallow rotation (Sadras, et al. 2002). Only a 0-5% increase in non-cereals in rotation occurred through the audit period as few reliable pulse or oilseed options were available. The normal practice of ‘long fallow’ has decreased as cropping intensity has increased (Appendix 11), resulting in less soil moisture being carried through to the winter cereals (can equate to 50 mm of moisture). This occurred through the 1980s and early 1990s, particularly in northern shires. An initial adoption of minimum tillage systems has declined and reliance on mechanical fallows and conventional tillage continues in a high risk cropping environment. It was also commented that a local wheat breeding program (Department of Natural Resources and Environment) had successfully bred varieties for the Wimmera in the south, but that in the northern Mallee, a high proportion of crops were planted with South Australian bred varieties, e.g. Frame.

In the Wimmera, yield trends were typically in the 0-45 kg/ha/year range, but were negative in the large Hindmarsh shire. Considering the low yield variability (Appendix 4), and the large 10-35 per cent increase in crop diversity (Appendix 7), a better result would have been expected. However, discussions with agronomists (Belford, Eastwood, Unkovich, Glasgow and Van Rees) highlighted a number of factors working against higher wheat yields in the Wimmera and southern Mallee:

1. The large trend to more non-cereals was related to the fact that pulse grain legumes (chickpeas, peas and more latterly lentils) were grown as a ‘cash crop’. These legumes are less effective at N fixation than pasture phases and other grain legumes (McNeil and Unkovich 2000). In the Wimmera, grain legumes produced large amounts of grain, high harvest index, high export of N in grain, and little stubble. This meant that relatively little N is recycled, and in some cases a negative balance is found (Belford, Unkovich, personal communication). N fertiliser application rates for wheat following legumes need to be > 30 kg N/ha to see any benefit in terms of increased yield (McNeil and Unkovich 2000), something not regularly observed in this region (NLWRA 2001).

2. The highest increase in cropping intensity in the Australian grain-belt (Appendix 11) meant more N-fixing pastures were taken out of rotation. The normal two-year break prior to wheat was replaced by continuous legume/wheat rotations, but herbicide resistance started being a problem in the early 1990s.

3. In the 1990s, the high prices received for pulses and oilseeds meant that farmers switched their best land from growing cereals to other crops.

4. High frost risk in the south has meant many farmers tend to delay seeding until June to reduce frost damage (O’Leary et al. 1985).

Minimum tillage systems have been a major contributor to productivity growth (Knopke et al. 2000). Shires that have higher trends, such as the west Wimmera and north-eastern areas, have switched from sheep to a greater emphasis of cropping, with minimum tillage being more utilised and sodic soils being more suited to gypsum application. The highest gypsum application in the country occurs in the Victorian Wimmera (SCARM 1998), but the benefits of this are seen more in the non-cereal phases which were not assessed in this report.

3.1.6 New South Wales

Prior to 1993, Hamblin and Kyneur (1993) and Cornish et al. (1998) found that high yield trends had occurred in the south-east of the NSW wheatbelt, with low to negligible trends being recorded elsewhere, particularly in the north. In this study, yield trends in south-eastern regions of the State have continued to be some of the highest in the country, but large increases have more recently occurred in most northern shires and the irrigation region in the south. These regional patterns tend to match yield variability patterns and three zones can be...
identified:

(1) Southern and south-eastern areas (south of Griffith) where very large increases in yields of the order of 50-100 kg/ha/yr were calculated, with the highest trends generally in irrigation areas, or the wetter eastern edge of the wheatbelt where more acidic soils are found (NLWRA 2001).

(2) Central zone (roughly between Griffith and Dubbo) where yield variability is high and yields increased from 15-30 kg/ha/yr in the west, ranging up to 45-60 ha/yr in the east.

(3) Northern zone (north of Dubbo) where yield trends are consistently 45-75 kg/ha/yr, with some very high yield trends around Tamworth.

Discussions with agronomists (Angus, Hayman, Kneipp, Brennan; personal communication) highlighted regional differences in management practices that have been adopted over the audit period.

In south-eastern NSW, a 15-25 per cent increase in the proportion of land planted to non-cereals consistently occurred through the shires with the highest yield trends (Appendix 7). A number of sources emphasised the important role that canola and lime application has played in this region. Besides the important role of soil cleaning, the deep rooted canola plants assisted in the development of pathways for subsequent wheat plants to extract more water from the soil (Angus et al. 2001). The development of Triazine-tolerant canola has enabled a more successful weed control program, particularly grass weeds which are prevalent in this region. The largest application rate in the country of lime, dolomite and gypsum has occurred in this area (SCARM 1998) with large yield responses on the highly acidic soils. On a six-year annual pasture-crop rotation, wheat crops produced 1.6 t/ha more grain on limed treatments than on the unlimed treatments (3.6 v 2.0 t/ha) (Li et al. 2001). The application of lime has been successful in this region for a number of reasons. Firstly, lime increases the pH of the highly acidic soils. Secondly, it makes the high aluminium concentrations in clay soils non-toxic which greatly assists canola, and to a lesser degree, wheat. Further, lime application has meant that the benefits of N fertiliser application have been better realised, which has further encouraged higher fertiliser usage. Providing optimum N fertiliser, or suppressing cryptic root diseases/parasites with break crops, increased yields 10-20 per cent above control yields (Angus and van Herwaarden 2001; Harris et al. 2002).

In the southern shires that have irrigation, there is a consistent very large increase in yields greater than 75 kg/ha/yr. Irrigation in this area was traditionally applied to rice, but recent increases in irrigation area have gone more into growing wheat. Along with this, there has been better N testing and consequent nutrition of wheat plants. A high-input high-output approach was tried by many farmers as extension agencies in the area promoted the ‘five tonne club’ (Storey 2001). However, inconsistent higher yields and losses from pre-harvest rain damage have caused losses in income in more recent years (Storey 2001). Productivity in southern NSW has also increased through the breeding of higher yielding, rust resistant varieties and minimum tillage farming (Knopke et al. 2000).

In central NSW, reduced tillage has not been as widely adopted as other areas and the increased practice of wheat/wheat cropping programs has meant less water is carried through into crop growing seasons. An increase in the rate of N application has occurred, but a combination of poorer soils and higher climate variability has reduced potential yields in wet and dry years. Higher N rates have not been profitable in very dry years. Southern shires in this region have incorporated more canola, but northern shires have had less than a 5 per cent increase in crop diversity.

The reversal in the performance of wheat growers in northern NSW, from negligible/negative trends, to solid increases in yield in the late 1990s is dramatic. The major driver of this has been the doubling of N fertiliser sales in northern NSW from 1992 to 1997 (Hayman and Alston 1999). Many farmers applied no fertiliser in the past as the deep black soils were naturally fertile, but a decline in soil fertility and adoption of better management practices
have contributed to the large increase in N application rates in the period 1992-1996 (Hayman and Alston 1999). Most importantly, farmers have come to understand that if a drought occurs in either the summer (sorghum) or winter crops (cereals, legumes), then N is carried through to the following seasons crop (Hayman, personal communication). This nullifies one of the main downside risks with higher fertilisation application. A higher price for high protein wheat also encouraged N fertiliser application.

Other major changes in the most north-western shires (e.g. Moree Plains, Walgett, etc.) has been the 5-10 per cent increase in cropping intensity. This has coincided with an increase in summer cropping, particularly sorghum, and to a lesser degree sunflower and cotton. Sorghum, like canola, acts as a break crop and cleansing agent for root diseases such as crown rot. Winter pulses also control root diseases, but the cost of growing these crops has limited their uptake rate. Minimum tillage practices have also become widely adopted and this has improved soil structure and reduced soil compaction. A reduction in the price of glyphosate has meant that much better weed control has occurred in fallow. These last two factors have contributed to more soil moisture being available for wheat crops. Controlled traffic farming systems have also become popular and reduce soil compaction problems under crops. The success of sorghum/wheat rotations and the increase in cotton (Liverpool Plains) has contributed to higher farm profits (Appendix 12), which can be used to pay for high input farming practices.

3.1.7 Queensland

Wheat yield trends in Queensland between 1982 and 1997 were patchy and mainly very low (Appendix 1). Hamblin and Kyneur (1993) found positive yield trends in northern Queensland and the wetter areas of the Darling Downs, but very low trends in central and south-western shires. Cornish et al. (1998) found there was no significant trends in yields between 1975 and 1993, except for a few shires in the east. In Appendix 1, yield trends were very low (decreasing to 15 kg/ha/yr) in northern and central shires, mixed in the Darling Downs to Roma region, and low (<30 kg/ha/yr) in the south-west.

If a change in farming practices were considered alone, Queensland should have had some of the most positive yield trends. During the 1980s and 1990s, Queensland had the largest Statewide swing to earlier sowing as the recommended planting window was shifted a month earlier in the north, and one to four weeks earlier in the more frost-prone regions in the south (Woodruff, personal communication; Stephens and Lyons 1998b). The largest change from conventional sowing to minimum and zero tillage methods occurred in Queensland during the 1980s and 1990s (Wallwork 2001). More stubble retention would have improved the retention of summer rainfall in the soils and would have also reduced the occurrence of sheet erosion. Further, the highest mean yield gains from semi-dwarf varieties occurred in Queensland (Brennan and Fox 1995), although most occurred in the late 1970s, with only a 10 per cent increase wheat planted to semi-dwarf varieties from 1982-97 (Brennan, personal communication). A positive change in Queensland has also been the reduced frequency of severe frosts and an increase in minimum temperatures over the audit period (Stone et al. 1996). Nicholls (1997) attributed 30-50 per cent of the increase in average Australian wheat yields since 1952 to climate trends, with increases in minimum temperature being the dominant influence. This assessment appears to overstate the influence of low minimum temperatures as the smallest increase in yields has occurred in Queensland (Figure 1.1) where the frequency of frosts has been most reduced.

These positive changes have not translated into large yield increases and there is a noticeable step-down in yield trends as one crosses from NSW (Moree Plains) to Queensland (Waggamba). Agronomists in Queensland (Freebairn, French, Spackman, Woodruff, personal communication) noted regional variations in management across Queensland and between NSW and Queensland:

- The border between Queensland and NSW was close to the edge of the region that was most affected by a persistent four-year drought that affected Queensland mainly between 1991 and 1994 (also 1995 in some areas). Partly as a result of this drought, the
coefficient of variation (CV) in yields in Moree Plains (NSW) was only 0.28, but increased to 0.38 across the border (Waggamba Shire), and even greater further north, e.g. Taroom 0.69. In northern and central shires the extreme climate variability affected the adoption of higher input management practices. Farmers in Queensland started experimenting with higher N fertiliser rates in the early 1990s at the same time as NSW farmers. However, the prolonged exceptional drought through the early 1990s (Stephens 1998) severely affected farmers financially (Appendix 12). The amount of fertiliser sold in southern Queensland dropped from 1990 to 1995, and it wasn’t until 1996, a very good year, that Queensland farmers started to significantly increase N inputs (Hayman and Alston 1999). Based on a survey of 22 farms, Cornish et al. (1998) concluded that productivity growth appeared to relate to N fertiliser application rates varying from 20-40 kg/ha/yr.

- An additional negative impact on regional yields in Queensland has been the recent dramatic increases in root diseases such as crown rot, and to a lesser degree common root rot. This increase has coincided with stubble retention rates increasing from negligible areas to 50-70 per cent of crop areas with the increased use of minimum tillage (Wildermuth, personal communication). This problem is more pronounced in southern areas of the State as a wider mix of crops in rotation (sunflowers, sorghum, chickpeas, mung beans) reduce the occurrence of disease in the north (Spackman, personal communication). Growers with larger farms are better able to manage disease with a rigorous crop rotation system.

- There has been little change in the cropping system in terms of crop rotations with a negligible change in non-cereal percentage occurring from 1983 to 1996 (Appendix 7). Low non-cereal percentages (< 10 per cent) are common in Queensland (Appendix 6), but do not differ from northern New South Wales.

A large reversal in trends in northern Queensland (central highlands) to what was found by Hamblin and Kyneur (1993) appears to relate to a very high yield variability (Appendix 4) and a sequence of poor planting opportunities in the early 1990s (Stephens 1998). In this opportunistic region, farmers geared up their inputs in these drought years to the following summer crops, e.g. sunflower and sorghum. With relatively high soil N reserves in this region (Graham et al. 1981; Hamblin and Kyneur 1993), a negative N balance found in this region between 1992 and 1996 in the NLWRA (2001) (Appendix 9), suggests that the soil fertility had run down in this region. Spackman (personal communication) noted that by the mid-1990s soil N levels had fallen to critical low values, but that farmers had increased N inputs from 1997 onwards (after the audit period). This latter change was encouraged by more water being available to plants from zero-tillage which enhanced the crop response from N application.

These findings suggest that small increases in N fertiliser application and the severe climate variability have had a large impact in limiting yield increases. Severe climate variability directly reduces yields, but also discouraged higher N inputs via inconsistent increases in yield from increased N (Strong et al. 1996). Restricted sowing opportunities and reduced cash flow for crop inputs also reduce farmers’ capacity to increase yields. A higher rate of root disease (associated with increased minimum tillage) may also be reducing trends in a significant way.
3.2 Trends in yields - other grains

3.2.1 Barley yield trends

Trends in shire barley yields (Appendix 13) are generally lower than trends in wheat yields, but tend to match the regional variations found in wheat (Appendix 1). The correlation between wheat and barley yield trends for all shires in the study was 0.58. Higher trends (> 45 kg/ha/yr) have occurred in south-eastern and north-western areas of the New South Wales grainbelt, southern and north-western areas of the Western Australian grainbelt, and mostly wetter areas in South Australia and Victoria. In Queensland, very small areas are planted to barley and negligible to decreasing trends were found from 1982-96, except for a few south-eastern shires in the Darling Downs.

One major reason barley yields have not increased as much as wheat, is because farmers have restricted increased N inputs so as to make sure that the barley protein does not exceed that required for malting barley. A price premium applies for malting barley and a steep drop in price occurs if the protein is too high. As returns on feed barley became unprofitable, farmers switched more to growing malting barley and attaining the right protein. The fact that barley tends to be grown on poorer sandier soils would also limit yield trends.

Trends for barley are approximately similar to those for wheat in the wetter more frost prone areas of southern Western Australia, southern New South Wales and southern Victoria. Since barley is generally more tolerant of waterlogging and frost, farmers are more likely to pay more attention to better management and applying higher inputs. In much of the southern half of Victoria trends in barley exceed those for wheat as there was more of a tendency for barley or canola to have a better position in the sequence in crop rotations (Glasgow, personal communication).

3.2.2 Oats and other cereals

In Appendix 14, calculated trends in oats and other cereals were generally lower than those for wheat (Appendix 1) and barley (Appendix 13), and probably reflect the lower financial returns obtained for oats in many areas. A major factor affecting trends in oats was the shift in focus in many areas to hay production in more recent years. In the 1980s oats was predominantly grown for grain, but in the 1990s there has been more of an emphasis on growing oats for export hay production (Lewis, personal communication). The correlation between wheat yield trends and trends in oats and other cereals and was only 0.4.

The regional pattern in yield trends in oats and other cereals tended to match the regional pattern of rainfall received during winter. Higher trends (> 60 kg/ha/yr) were found in a few pockets in the wetter areas of south-western Western Australia, central South Australia, far south-eastern South Australia and the far south of New South Wales. These regions tend to be cool, wet environments where waterlogging and/or frost is more frequent, and where oats generally do better than other cereals. Yield reductions associated with waterlogging are less for oats than other cereals, and with a stronger seed coating in a less compact head, frost damage is less likely. In drier environments, oats do not perform as well as wheat or barley and less emphasis has been placed on increasing yields. Very low to negligible trends were observed in northern and inland shires that receive smaller amounts of winter rainfall. Lowest trends were observed in Queensland, much of northern New South Wales, large areas of the Eyre Peninsula (South Australia) and the far north-east of Western Australia. In much of north-eastern Australia the low financial returns from oats and other cereals has meant that very small areas are planted to these crops.

Adding to this pattern of yield trends have been special contracts for high quality milling oats in areas where larger and better quality oat grains were grown. During the 1990s, milling companies began offering special contracts for higher protein milling oats in areas where the highest yield trends have been observed (around Narrogin, south-west Western Australia and...
With financial incentives, farmers in these areas got more serious about growing oats as a cereal for grain. Nitrogen began to be applied and weed management became more of a priority as less weeds increased water supply and reduced losses to take-all. Herbicide application increased and this was supplemented by mechanical control of weeds by increasing sowing densities. Oats being a quick growing crop, can smother ryegrass if planted at a high enough density (Venn, personal communication). Plant breeding also contributed to better yielding varieties in most southern States.

### 3.2.3 Sorghum yield trends

Sorghum is predominantly grown in the northern cropping zone of Queensland and northern New South Wales (Appendix 15). In a similar way to wheat, there has been a division in sorghum yield trends as one goes from northern New South Wales to Queensland. Marked increases in yields (> 60 kg/ha/yr) have occurred for most of northern New South Wales, whereas in Queensland the increases have generally been < 30 kg/ha/yr and in many cases negligible.

In northern New South Wales, a dramatic increase in N application on sorghum occurred as farmers noticed there was no downside risk in applying higher rates (Hayman, personal communication). If a dry summer occurred and sorghum yields were reduced, the remaining soil N would mostly carry over into the following winter wheat crop. If more N was applied in better years, the higher yielding sorghum crops made good financial returns and were less affected by wet harvests that tended to plague higher yielding wheat crops. Sorghum harvest occurs at the end of summer when rainfall is decreasing, whereas wheat harvest is occurring in October as rainfall is increasing. As with wheat, better weed and tillage management techniques have also contributed to higher sorghum yields. Farmers on the eastern edge of the grain belt in northern New South Wales increased sorghum plantings during the 1990s as they concentrated more on cropping (Wuldermuth, personal communication).

Across the border in Queensland, the high yield variability and serious droughts of the early 1990s restricted an increase in N application rates. Sorghum yield trends would also have been negatively impacted by a switch to increased summer cotton plantings on the better cropping land. This was especially the case on the Darling Downs where very low to negative trends were found. Higher returns for cotton meant that sorghum was treated more as a secondary crop and planted on poorer quality land. However, trends >40 kg/ha/yr did occur in east central shires around Roma as sheep and cattle producers became better sorghum croppers during the 1990s.

### 3.3 Water use efficiency (WUE)

There are many factors reducing crop yields below their potential. French and Schultz (1984a, 1984b) discuss how waterlogging, weeds, pests, diseases, nutrient deficiencies, agronomic deficiencies (time of sowing, etc.) extreme temperatures, lodging and soil erosion can reduce yields. Subsoil constraints, drainage, run-off, acidity, water repellency, surface ponding and a host of other factors can also cause crops yields to be lower than their potential. On an inter-annual basis, WUE fluctuates considerably and is generally higher in water-limiting situations and lower in wetter years. In Western Australia, very low WUE in wetter years is associated with waterlogging and drainage losses (Hoyle and Anderson 1993; Stephens 1997). In this study we focus on regional patterns in water use efficiency.

#### 3.3.1 Wheat water use efficiency

The average WUE for wheat (Appendix 16) was generally higher where soils had good waterholding capacities, yield variability was low (Appendix 4) and rainfall was reliable between June and September (Appendix 5). The large-scale patterns in WUE reflect management efficiencies and different aspects of the simple water budget. Generally, low (< 40 per cent) water efficiencies were found in the wet south-west of Western Australia, northern Eyre
Peninsula (South Australia) and the north-eastern GRDC zone (northern New South Wales and Queensland). As expected, the highest WUE (> 80 per cent) was recorded in the irrigation areas around Griffith in southern New South Wales. Here, extra water is added to crops at critical times which is not accounted for in this simple modelling approach. Quite reasonable WUE (> 60 per cent) also occur through central parts of the Western Australian wheatbelt, in wetter areas of South Australia, and in the Wimmera region of Victoria.

Determination of WUE in the north-eastern zone is affected by the simplicity of the modelling approach used. The soil profile is assumed to be dry on 1 October (an underestimation of moisture), but then a fallow water balance accumulates moisture through summer/autumn to sowing. If a summer crop was grown or weeds were prevalent then extra water would carry through than what would normally be expected (overestimation of moisture). However, given that the proportion of land planted to summer crop is low for most inland shires, and a short summer fallow is usually sufficient to recharge soil profiles (Nix 1975), the overestimation should not be too great. Where fallowing is carried out, there should be even more water accumulation than what the model calculates. A 60 per cent WUE in the Darling Downs (where summer crops are more prominent) suggests that the trend to lower WUE further west (where summer crops are a small proportion of cropping) is realistic. Cornish et al. (1998) also found low WUE across north-eastern cropping areas, which agreed with farmer perceptions in the region.

When analysing regional patterns of WUE it is once again important to recognise the very different crop water environments across the Australian wheatbelt. In Figure 3.9, the mean WUE over the 1993-97 period is plotted against mean shire yields through the audit period. In Figure 3.10 the WUE is plotted against the variability in yields. In terms of mean yields, WUE increases with mean yields in Queensland and south-eastern Australia (but to a smaller degree), and actually decreases with higher yields in Western Australia. This result reflects the fact, that as rainfall distribution becomes more winter-dominant, the usefulness of high winter rainfall decreases (Stephens and Lyons 1998a). The increasing scatter in the relationships between mean yield and WUE with the clockwise progression around the wheatbelt, shows the increasingly variable usefulness of growing season rainfall and the importance of rainfall distribution in affecting productivity. Figure 3.10 shows WUE is not related to the narrow range in variability found across the Western Australian wheatbelt, but is increasingly related to variability as one moves more east and north in eastern Australia.

The strong relationship between mean yields and WUE ($r^2 = 0.71$) and variability and WUE ($r^2 = 0.67$) in Queensland, strongly confirms that water supply is important to farm productivity efficiencies. Significantly, the lowest WUE in the country was recorded in central Queensland around Roma, and northern Queensland around Emerald, where the highest coefficient of variation in yields was recorded (CV > 0.5). More arid variable regions (low yielding) have not utilised the water that has been available to them as stressed crops have not been able to get their roots down to extract deeper subsoil moisture. Allen and George (1956) discuss the need for good autumn rains in Queensland to enable planting, ensure good plant establishment and to link the surface and subsoil moisture. Good winter rains are needed for surface root development and the utilisation of topsoil N and spring rainfall (Allen and George 1956). In drought conditions farmers have used the crops for other purposes (e.g. stock feed, hay), further reducing measured yields and WUE at a shire-level. The higher WUE in higher rainfall shires in south-eastern Queensland would have probably benefited from a consistently more favourable water supply.

However, low WUE also extended into the northern half of New South Wales and covered the whole northern GRDC zone. In this zone, a large proportion of water supply comes from stored soil moisture from summer and autumn rains, suggesting that wheat does not extract all the moisture that is available in the rooting zone. Subsoil constraints in the heavier clay soils could play an important role in restricting root growth and water extraction. Fischer (1987) found that only 12-32 per cent of normal fallow rainfall, typically between December (the previous year) and June, is stored usefully as soil moisture in New South Wales. In Taroom...
Figure 3.9. Average water use efficiency of shire wheat yields (1993-97) compared to mean shire wheat yields (1982-97). Linear line of best fit for Western Australia (top line, $r^2 = 0.02$), logarithmic fit for south-eastern Australia (middle line, $r^2 = 0.11$) and Queensland (bottom line, $r^2 = 0.71$).

Figure 3.10. Average water use efficiency of shire wheat yields (1993-97) versus the variability in detrended wheat yields (1982-97). A linear line of best fit for Western Australia (left line, $r^2 = 0.02$), logarithmic fit for south-eastern Australia (centre curve, $r^2 = 0.31$) and Queensland (right curve, $r^2 = 0.67$).
shire, (CV in yields = 0.69) shallow soils reduced the buffering of water soil supply from summer rains and this would have contributed to the higher yield variability and poor performance (Freebairn, personal communication). Cornish et al. (1998) found low soil fertility, especially nitrogen and phosphorus, limited the capacity of crops to utilise available water (transpiration efficiency) across large tracts of the northern cropping zone. Subsoil constraints to root penetration in the B horizon are found in the duplex soils of southern New South Wales and northern Victoria (Greeves et al. 1994). In addition to soil water and nutrient constraints, the following factors all contribute to lower yields and production efficiency in the north-eastern wheatbelt:

- There is a higher probability of damage (lodging) to winter cereals from early summer rains in October (Allen and George 1956);
- Higher rates of root disease (Brennan and Murray 1998) and little planting of oilseed break crops to address this (although sorghum in rotation with wheat is beneficial);
- Widespread crop losses from frost and very high day temperatures are more likely (Single 1987);
- Higher rainfall intensities as one moves further north (Hammer 1983). STIN has a runoff function in the fallow period prior to seeding, but does not have such a function in the crop growth period when most rainfall infiltrates the soil.

In south-eastern Australia, haying-off is a problem that typically occurs as dense crop canopies and high levels of soil N are more common than the less dense canopies of crops grown in northern and Western Australia (Nicholls and van Herwaarden 1998).

Low WUE in the wetter western shires of Western Australia reflect deep drainage (water loss below the root zone) and waterlogging limitations to yield. A truncated winter rainfall distribution means that over 60 per cent of annual rainfall can fall in the three months June, July and August (Gentilli 1971). Asseng et al. (2001) show with the APSIM model that deep drainage increases linearly in the Western Australian wheatbelt with annual rainfall above 248 mm on deep sand, and 359 mm on a clay soil. In the northern half of the Western Australian wheatbelt there is a predominant sand-plain along the coast and low WUEs coincide with higher annual rainfall and drainage losses (Asseng et al. 2001). Soil acidity is also high (pH < 5.5, NLWRA 2001) with aluminium toxicity impairing root growth and the uptake of water and nutrients.

In the wetter south-west of Western Australia, Wigley and Tu Qipu (1983) and Stephens and Lyons (1998a) showed shire yields are negatively related to high winter rainfall when waterlogging in the root zone reduces yields. High winter rainfall reduces plant emergence, increases stress on plants when soil oxygen is depleted, increases interactions between salinity and waterlogging, N leaching, and diseases - all of which reduce potential yields (Belford et al. 1992; Dracup et al. 1992; McFarlane et al. 1992). Waterlogging reduces the potential yield by 30-80 per cent for many crops and pastures in the > 400 mm rainfall zone (McFarlane and Williamson 2002). In addition, high subsoil bulk density and penetration resistance in the B horizon of duplex soils are associated with poor shoot and root growth in Western Australia (Dracup et al. 1992; Tennant et al. 1992). For the large areas of duplex soils in this State, low water-holding capacities mean that there is little water buffering available. Moisture stress conditions (waterlogging/insufficient water) can therefore develop rapidly affecting crop yield potential and WUE.

In South Australia, the areas with low WUE coincide with the highly calcareous and sodic subsoils found in the upper north of the Eyre Peninsula and the upper north of the south-east (NLWRA 2001). Water repellency is a well recognised problem in these areas, affecting nearly a half a million hectares in the upper south-east alone (WANTFA 1999). The low adoption of new technology (nutrient management, increasing crop diversity) in these drier
areas would also add to disease problems, nutrient deficiencies and overall WUE. Confirming the importance of soil constraints in the Mallee regions of South Australia, Victoria and New South Australia, Sadras et al. (2002) found sodicity, alkalinity, salinity, and boron toxicity reduced yields by reducing the availability of stored water and reducing the benefit of initial and applied N.

The spatial relationship between trends in yield (Appendix 1) and WUE (Appendix 16) was similar for many areas, suggesting that progressive farmers who have improved their management are best at using the available water supply. Exceptions to this rule are found in:

- Victoria where a high WUE and low trends relate to the fact that mean yields were coming off a high base before the audit period;
- Wetter areas of Western Australia where drainage and waterlogging losses are greatest;
- The far south-east of Victoria and New South Wales where highly acid soils (pH < 4.8, NLWRA, 2001) are found.

Finally, the high WUE in large parts of Victoria and South Australia is a good result given that the largest losses to wheat diseases in the country ($/ha) are found in these two States (Brennan and Murray 1998).

3.3.2 Barley water use efficiency

Barley has a tendency to outperform wheat, having a higher WUE, greater harvest index and greater dry matter production, particularly on fine textured soils (Simpson and Siddique 1994). However, with farmers placing less emphasis on higher barley yields than wheat, the measured yields and associated WUE are correspondingly lower (Appendix 17). The WUE of wheat and barley are related in many shires ($^2 = 0.55$, for all shires) and the regional pattern in WUE matches that for wheat. There does however seem to be more of a change in WUE between Victoria and the Mallee of South Australia. Highest WUE (> 50 per cent) is found in north-central South Australia, southern and central Western Australia, the irrigation area near Griffith (New South Wales) and the southern Darling Downs (Queensland). Lower barley WUE (<30 per cent) is found in inland shires in Queensland and New South Wales, and the wetter margins of south-eastern Australia and Western Australia.

3.3.3 Oats and other cereals (0a0C) water use efficiency

The water use efficiencies of 0a0C are lower again than for wheat and barley, but the regional pattern also matches those for wheat ($^2 = 0.59$ for all shires, Appendix 18). Very low values (< 20 per cent) occur where high crop yield variability is found (Appendix 4), which includes inland areas of Queensland, central New South Wales and most of the Eyre Peninsula (South Australia). In Western Australia, the WUE for 0a0C is much lower than wheat in the northern half of the wheatbelt and the Esperance shire (south-east) where much more emphasis is given to other crops.

With the WUE of the winter-grown wheat, barley and 0a0C varying in a similar pattern across the Australian grainbelt, it can be concluded that soil, climate and financial factors at a regional level affect the farmers’ ability to grow each of the different cereals efficiently. The drop in efficiencies from wheat, to barley, to 0a0C reflects the reduced financial returns farmers receive for barley and oats, and the lower priorities they place in increasing inputs and yields in these cereals.

3.3.4 Sorghum water use efficiency

Sorghum WUE is generally very low (< 40 per cent) for much of the summer north-eastern grainbelt (Appendix 19). Higher values (> 50 per cent) are found where sorghum is grown on the better quality deep soils of the Darling Downs in Queensland, and on the Liverpool Plains around Tamworth (New South Wales). Very high values (> 70 per cent) occur in the three
most southern shires in the study (Narromine, Warren and Dubbo) where small areas of sorghum are planted (<600 ha) and irrigation is applied.

The marked reduction in WUE in western cropping regions of Queensland and northern New South Wales, compared to those regions further east, appears to reflect grower attitudes about wheat and sorghum and climate constraints. Inland, wheat is considered the main crop and sorghum a second choice, which is grown half for grain, and half for fodder. With mixed farming and more livestock in inland areas, sorghum is more widely used for stock feed in drier years. Since sorghum is a ‘poor relation’ to wheat, less attention is given to weeds, less fallowing is done prior to seeding, and less fertiliser is applied as wheat (Freebairn, personal communication). As well, soils less efficiently store summer rainfall in inland Queensland than regions further east. In eastern regions, farmers have recently learnt how to obtain high sorghum yields and almost all sorghum is grown for grain (Freebairn, personal communication). In eastern regions the higher altitude and cooler environment (lower vapour pressure deficit) is favourable for high sorghum yields, whereas the evaporation rate is so high inland that the response of sorghum to N is minimal (Hayman, personal communication).
4. CONCLUSIONS AND DISCUSSION

This study highlights the complex interaction between weather, soil, management and economics in determining crop yields, yield trends and water use efficiencies.

1. Higher yield trends occurred where farmers have addressed the combination of soil constraints to production, including, in order of importance:
   (i) chemical constraints:
       (a) nutrients (fertilisers, N-fixation); and
       (b) soil acidity and sodicity (lime/gypsum); and
   (ii) biological constraints:
       (a) flora - weeds, root diseases; and
       (b) fauna - nematodes (break crops, e.g. canola in south, sorghum in north);
   and
   (iii) physical constraints (minimum tillage - infiltration, water storage, soil structure, erosion losses).

2. Climate constraints, particularly rainfall variability, has an overriding influence on yield trends as it conditions the risk farmers are prepared to take in applying higher inputs (fertilisers) and affects the profitability of non-cereals in rotation (canola, pasture/grain legumes).

3. General relationships with 1 and 2 become secondary in regions where wheat is not the most profitable crop in the rotation (e.g. cash crops in Victorian Wimmera, cotton in northern areas), or a more sustainable management practice occurs (shorter fallow in Victoria).

Through the audit period the Australian cropping industry has turned its performance around. Exporting countries in north America that were outperforming Australia (Hamblin and Kyneur 1993) showed a tendency for a levelling off in yields in the 1990s (Calderini and Slafer 1998), with Australia’s relative position in average yields improving (Knopke et al. 2000). It does not seem coincidental then, that while N inputs rose dramatically through the 1990s in Australia, world demand for N levelled off (Angus 2001) with a reduction in world cereal yield growth rates (Harris and Kennedy 1999). Higher N demand in Australia in the 1990s was driven by:

- An unrelenting decline in farmers’ terms of trade and minimal government support (in way of subsidies), meant Australian growers had to improve productivity in order to maintain profitability (Knopke et al. 2000). A current rule of thumb is that increasing yield by 15 per cent will double profit; a similar yield decline will eliminate profit (Hammer et al. 2001);
- In response to declining wheat protein (Hamblin and Kyneur 1993), premiums for higher protein wheats were offered by the Australian Wheat Board. Higher proteins were achieved with increased N fertiliser application. Reduced income variability/risk was a by-product, as higher protein tends to occur in drier years when yields are lower (when screenings are not a problem);
- Since the area of pasture decreased, increased N fertiliser was needed to satisfy the increased demand of cereals following break crops and of the break crops themselves, particularly canola (Angus 2001);
- An understanding that N fertiliser can persist in the soil through to the following summer crop in dry seasons in northern NSW (Hayman, personal communication); and
- New semi-dwarf varieties were more responsive to N than older taller varieties (Anderson 1992).
The question that needs to be asked is: Can this trend to higher input agriculture be sustained? Pardey et al. (1999) speculated that soil, climate and environmental constraints (land quality) are the main reasons why Australian farm fertiliser intensity is among the lowest in rich-country agriculture. This study confirms that high yield variability and soil constraints are major drivers of the amount of productivity growth. With higher levels of inputs and expenditure (herbicides, fertilisers, fungicides, etc.), there is now a greater risk of financial losses in poor seasons. Considerable losses occurred in south-eastern Western Australia when a severe frost in 1998 greatly reduced shire yield prospects from record yields to 25 per cent below average. Assistance from the government, in the form of Exceptional Circumstance (EC) funding, was delivered to farmers in this region, but only after a sequence of frosts, wet harvests and drought over a three-year period. Likewise, frosts and poor seasons in the late 1990s in Victoria, and wet harvests in eastern Australia (1998-2000), have contributed to losses and doubts over the long term viability of high input farming (Story 2001). Concerns about increasing herbicide resistance in grain legume/wheat rotations have also increased in more recent years. Alternative forms of weed control are now being promoted to reduce this problem.

It seems certain that an increased efficiency in the way inputs are applied, especially N, will be required. Soil deficiencies in any of N, P, K, S, Ca, Mg, or Fe depress plant growth, even when all others nutrients are well supplied (Loneragan 1997), so soil testing appears necessary. Better and more timely fertiliser application (liquid fertilisers, deep banding), soil additives that improve N uptake, N efficient varieties, raised beds, and precision agriculture all appear important. These, and previous technical advances (varieties, minimum tillage, more options in weed control, crop types, pastures) have meant farmers have been better able to undertake higher-input agriculture than previously, especially since revenue risk has been reduced through forward contracts and price premiums for better quality crops (Kingwell, personal communication). However, Henderson and Kingwell (2002) found greater gains in profitability are possible by improving allocative efficiency (mix of crops in relation to prices, especially canola) than technical efficiency (least inputs for most outputs). Climate affects both allocative efficiencies (relative yields for different crops) and technical efficiencies (relative returns on inputs, especially fertilisers). There are also signs that climate extremes related to El Nino-Southern Oscillation are related to price (Wylie and Gregory 1999; Chapman et al. 2000). Therefore, much value can be obtained from climate forecasts that can indicate climate extremes with good lead-time.

Accurate seasonal weather forecasting can reduce the exposure to climate risks by allowing grain growers to adjust their yield targets for different climate conditions. Woodruff (quoted by Nicol 1999) estimates that three-quarters of farm income comes from one-quarter of the years. Therefore, seasonal indicators that minimise the risks in bad years, and which enable farmers to capitalise on the occasional very good season, can optimise farm profit and reduce environmental damage to the land. Crop yield forecasting models that integrate soil moisture at sowing, and indicators such as the Southern Oscillation Index (SOI), can give improved early indications of yield prospects (Stephens et al. 1989; Stephens et al. 2000; Hammer et al. 2001), especially when the climate forecast relates to rainfall anomalies (Stephens et al. 1989; Stephens et al. 2000). Simulation models suggest that adjusting N fertiliser and cultivar with the phase of the SOI (Stone and Auliciems 1992) can increase cropping returns, and/or reduce risk (Hammer et al. 1996a). Other tools such as Rainman (Clewett et al. 1994) and Whopper Cropper (Nelson et al. 2002) can facilitate the application of the SOI in practical decision making and scenario planning. Such forecasts and models need promoting in more arid and variable regions if these areas are to keep pace with technology in more reliable regions.

During the 1990s, SOI based forecasts appear to have been widely adopted in north-eastern Australia, where the biophysical and socio-economic ravages of drought were high, and where climatologists, agricultural systems modellers and analysts, and extension staff joined forces with the rural community to provide tools and develop strategies that can improve management decisions (White 1999). This process seems to have been assisted by winter...
values of the SOI being most strongly correlated to Queensland wheat yields in the decade prior to 1996, than any of the six previous decades (Stephens et al. 2000). However, even in northern New South Wales, Hayman and Alston (1999) found 90 per cent of farmers seldom used the SOI in the 1990s. Between 1986 and 1995 the correlation between winter SOI values and NSW State wheat yields fell to 0.06, compared to 0.71 in the previous decade. A similar change occurred in other States. Most existing seasonal forecasts only provide a limited one to three month lead-time (Smith 1994), and have limited skill prior to the end of autumn (Barnston et al. 1999). Unfortunately, the peak demand for forecasts is February to early autumn when primary industries are committing resources for the following months or year (Johnson 1994; Allan and Heathcote 1987). Recently derived indicators from the southern mid-latitudes do however show promise at predicting the majority of extreme El Niño/La Nina with longer lead-time (Stephens and Lamond 2001), and show promising skill (Smith 1994). Stephens and Lamond (1999) found that five of the seven most severe El Niño-Southern Oscillation (ENSO) droughts to affect eastern Australia (1957, 1965, 1972, 1982 and 1997) could have been predicted in the August-October period in the year before they developed.

In summary, this report has highlighted many improvements that have, and are being made, in the Australian grains industries. Cropping has entered a period of consolidation as productivity gains have increased at a greater rate. This would not have been possible without one of the highest agricultural R&D spending per capita (or per agricultural worker) in the world (Pardey et al. 1999). The successful lifting of productivity in the cropping industries in Australia in the 1990s has meant this research has brought big dividends. Farm business profits in cropping have improved (ABARE 2000) and Australia has lifted its share of world wheat exports from 12.8 per cent (1977-81) to 16.4 per cent of the trade in 1996-2000 (ABARE 2001). To maintain this trend technological improvements must continue, however future developments should focus on the unique regional pattern of climate and soil constraints highlighted in this report and in the NLWRA (2001). Water-supply and N deficiencies appear to be most limiting factors to crop production in Australia, but acidity, sodicity and diseases are also major limitations. All these factors and associated risks must be addressed systematically if relative production efficiencies are to improve further.
5. RECOMMENDATIONS

This project relied on annual census data of shire-level crop production, area and yield. Annual data is necessary to calibrate the yield-forecasting model STIN and determine technological increases in yield. It will not be possible to update this study in the future without annual census data.

- **Recommendation 1:** For continuing assessments of the success of funding applied to agricultural research, an annual agricultural census should be re-commenced to collect all crop production and area data at a shire level.

This report also drew attention to the importance of regional nutrient data, both fertilisers, and N fixation from legumes. These data, plus data on soil conditioners (lime, gypsum, etc.) need to be monitored annually on a shire-level basis to answer the following questions:

(i) What factors contribute to yield trends and by how much?

(ii) Where can research and extension be targeted better to assist farmers to reach their potential yields more profitably?

- **Recommendation 2:** To determine factors contributing to technological increases in yield, shire-level nutrient, lime and gypsum data needs to be collected by the fertiliser industry on an annual basis.

This report has found that plant breeding has played an important role in the steeper increase in yields found in some regions. In Western Australia and South Australia, studies have suggested that new varieties have contributed 32-35 per cent of yield increases (Black 1998; Anderson, 2002), however others would suggest a 50/50 split of benefits to breeding and better management.

- **Recommendation 3:** The contribution of plant breeding to higher yields needs to be better defined at a State and regional scale, especially in Victoria, New South Wales and Queensland. Breeding needs to be done on the basis of regional limitations in soil, climate and water supply.

Regional trend patterns show that some regions have been much more successful at lifting crop production. Reasons why best management practices are not adopted at a regional scale need to be examined in the context of rainfall reliability, yield variability and soil constraints. Price risk affects all growers, but climate and income risk varies considerably at a regional level.

- **Recommendation 4:** Reasons why best management practices are not adopted at a regional scale need to be examined in the context of climate variability (yields, grain quality, harvest damage) and soil constraints (acidity, sodicity, salinity, soil diseases). The most limiting factors to production need to be defined at a regional level and best management options explored. The role of extension and farmer groups in adopting technology needs defining, as do farmer attitudes to new technology.

With farms becoming bigger and a trend to high-input agriculture, farmers will be more vulnerable to large losses in extremely dry (low yields) and wet years (disease, grain damage). Long-range indicators that predict these extreme events with more lead-time are needed to reduce financial and environmental damage.

- **Recommendation 5:** Long-lead forecasts (> six months lead-time) of extreme droughts and wet periods need further research. More specific indicators that are relevant to southern Australia need to be outlined.

Seasonal variability affects all growers, but in varying frequency and intensities, tactical management tools have a great potential to assist farmers move beyond the simple ‘rule of thumb’ decision making processes that they have been used to. However, the marked
variation in yield variability across Australia suggests that these tools need to be targeted at the most variable environments in each State defined in Appendix 4.

- **Recommendation 6:** Simple tactical decision support tools need to be promoted across the whole Australian wheatbelt, especially in areas of higher yield variability where they would most benefit tactical input management.

A trend to higher input agriculture must coincide with an improvement in nutrient efficiencies if the trend is to be sustainable. Farmers can reduce losses in poor seasons and reduce overall input costs if fertilisers are used more efficiently.

- **Recommendation 7:** Better technologies (management and varieties) need developing to improve the nutrient efficiency of crops and reduce nutrient losses to the environment.

The implementation of these recommendations would assist in increasing productivity, improving production efficiencies, improving farm profits, and form the basis of proper monitoring of the sustainability of technological advances.
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Thus report would not have been possible without this assistance and is gratefully acknowledged.
7. REFERENCES


8. APPENDICES

APPENDIX 1. TRENDS IN SHIRE WHEAT YIELDS 1982-1997

Trends in Shire Yields
Wheat 1982 - 1997

Western Australia

Statistical Local Government Areas

Trends
kg/ha/yr

> 90
75 to 90
60 to 75
45 to 60
30 to 45
15 to 30
0 to 15
steady/decreasing

Geraldton
Detwiler
Medindie
uitsbimir
Bunbury
Lake Grace
Elperance

South Australia

New South Wales

Queensland

Canberra
Melbourne
Sydney
Brisbane
Canberra
Mackay
Darwin
Adelaide
Perth
Brisbane
Mackay
Darwin
Adelaide
Perth
APPENDIX 2. THE PERCENTAGE INCREASE IN SHIRE WHEAT YIELDS 1982-1997

Trends in Shire Yields
Wheat 1982 - 1997

% Increase
> 90
75 to 90
60 to 75
45 to 60
30 to 45
15 to 30
0 to 15
steady/decreasing

Statistical Local Government Areas

Western Australia

Geraldton

Esperance

Perth

Bunbury

Lake Grace

South Australia

Ceduna

Port Augusta

Port Lincoln

Adelelaide

South Australia

New South Wales

Canberra

Melbourne

Sydney

Queensland

Brisbane

Mackay

Queensland

Darwin

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APPENDIX 3. AVERAGE SHIRE WHEAT YIELDS 1982-1997

Average Shire Yields
Wheat 1982 - 1997

Yield
< 1.00
1.00 to 1.24
1.25 to 1.49
1.50 to 1.74
1.75 to 1.99
2.00 to 2.24
2.25 to 2.49
> 2.49

Statistical Local Government Areas
Variability in Shire Yields
Wheat 1982 - 1997

Coefficient of Variation

- < 0.10
- 0.10 to 0.16
- 0.17 to 0.23
- 0.24 to 0.30
- 0.31 to 0.37
- 0.38 to 0.44
- 0.45 to 0.51
- > 0.51

Statistical Local Government Areas

Western Australia

Perth
Geraldton
Bunbury

New South Wales

Sydney
Canberra

Queensland

Mackay
Brisbane

SOUTH ADELAIDE

Adelaide
Port Lincoln

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APPENDIX 5. RELIABILITY OF JUNE-SEPTEMBER RAINFALL - 20 MM EACH MONTH
(SOURCE: RAINFALL WIZARD, BRS)
APPENDIX 6. WINTER CROP DIVERSITY 1983/84-1996/97

Crop Diversity: 1997 Non-Cereal Percentage

Percentage of total winter crop
- 0
- 0.01 - 5
- 5.01 - 10
- 10.01 - 15
- 15.01 - 20
- 20.01 - 25
- 25.01 - 30
- 30.01 - 35
- Greater than 35

0 1000 Kilometers
APPENDIX 7. CHANGE IN CROP DIVERSITY 1983/84-1996/97
(SOURCE: J. WALCOTT, BRS)

Crop Diversity: Change in non-cereal percentage (1996/97 - 1983/84)
(SOURCE: NLWRA. 2001)

1996/97

MEAN 1992-1996

<table>
<thead>
<tr>
<th>kg N/ha</th>
<th>Slightly positive (10 to 50)</th>
<th>Moderately positive (50 to 100)</th>
<th>Highly positive (100 to 250)</th>
<th>Extremely positive (Greater than 250)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Negative (Less than -50)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slightly negative (-10 to -50)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Neutral (0 +/- 10)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non agricultural area</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

NITROGEN (N) BALANCE (kg N/ha)
All land uses combined

57
APPENDIX 11. CHANGE IN CROPPING INTENSITY 1983/84 TO 1996/97. (SOURCE: L. CHAPMAN, ABARE)
(SOURCE: L. CHAPMAN/ M. CHARGE, ABARE)

Farm performance
Farm business profit: 5 year average 1992-93 to 1996-97:

- Insufficient data
- Over 100000
- 50000 to 100000
- 0 to 50000
- -10000 to 0
- -30000 to -10000
- -50000 to -30000
- Under -50000

ABARE
Innovation in Economic Research

Trends in Shire Yields
Oats and other cereals 1982 - 1996

<table>
<thead>
<tr>
<th>Trends</th>
<th>kg/ha/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 90</td>
<td></td>
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<tr>
<td>75 to 90</td>
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<tr>
<td>60 to 75</td>
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<tr>
<td>45 to 60</td>
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<td>30 to 45</td>
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<td>15 to 30</td>
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<tr>
<td>0 to 15</td>
<td></td>
</tr>
<tr>
<td>steady/decreasing</td>
<td></td>
</tr>
</tbody>
</table>

Statistical Local Government Areas

Spatial Resource Information Group
APPENDIX 15. TRENDS IN SHIRE SORGHUM YIELDS 1982-1996.

Average Water Use Efficiency (WUE)
Wheat 1993 - 1997

Average Water Use Efficiency (WUE)
Barley 1992 - 1996

Efficiency (%)

- > 80
- 70 to 80
- 60 to 70
- 50 to 60
- 40 to 50
- 30 to 40
- 20 to 30
- < 20

Note: The map shows the average water use efficiency for barley across Western Australia and South Australia during the period 1992-1996. The efficiency is color-coded to indicate different percentage ranges.
APPENDIX 18. AVERAGE WATER USE EFFICIENCY - OATS AND OTHER CEREALS (1982-1996)

Average Water Use Efficiency (WUE)
Oats and other cereals 1992 - 1996

Efficiency (%)
- > 80
- 70 to 80
- 60 to 70
- 50 to 60
- 40 to 50
- 30 to 40
- 20 to 30
- < 20

[Map showing average water use efficiency for oats and other cereals across different regions in Australia, with color-coded efficiency levels.]