Risk management of wheat in a non-stationary climate: frost in Central Queensland

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Abstract: The viability of cropping systems is extremely sensitive to variations in climate, requiring adjustments not only in crop management but also in land use with changing environmental and market conditions. The Emerald region in Central Queensland is at the most northerly margin where winter cropping occurs in Australia. Any impact of possible climate change is likely to manifest itself first in such marginal environments. Considering the current debate on climate change impacts, a pertinent question is: can the Central Queensland wheat industry cope with the likely changes in climate and remain viable? Historically, one of the key sensitivities has been the limitation that frost places on winter cropping, particularly wheat, as the date of the last frosts limits the opportunities for early-maturing crops that would otherwise mature under milder conditions, hence decreasing the likelihood of yield reductions caused by water limitation during grain filling. Strong trends in reduction in frost incidence over the past century have already been documented for this region. Here we report results from a simulation study that quantifies the economic value of using frost risk management practices that explicitly take such non-stationary trends in climate into account. The documented trends are likely to continue and wheat producers could benefit from taking such information into account. However, the industry is currently not proactively engaged with the issue even though changes in their own practices suggest that they have already responded autonomously.

***Keywords**: frost, climate variability, climate change, Australia, cropping systems, wheat*

1. INTRODUCTION

There is now firm evidence that in addition to the observed year-to-year climate variability, there are also trends in both observed and derived climate variables (e.g. increases in minimum temperatures, changes in the degree of rainfall variability etc.) that result in a non-stationary climate (Suppiah and Hennessy, 1998; Collins et al., 2000). These trends are the combined results of low-frequency climate variability as well as anthropologically induced climate change (Meinke et al., 2003). The consequences are measurable and profound.

Global temperatures have risen at an unprecedented rate during the 20th century (IPCC, 2001). This has implications for agriculture. For example, the number of frost days across most of Australia has reduced considerably since the 1950s. Dates of first and last frosts have become later and earlier, respectively (e.g. Stone et al., 1996). This has already changed variety choice and planting dates for wheat in areas with marginal frost risk such as Central Queensland (Meinke et al., 2003). However, the trends are masked by the high degree of background climate variability.

Good risk managers can no longer afford to dismiss this evidence - appropriate risk management strategies need to take both climate variability and trends into account in order to achieve the best possible outcomes (Howden et al., 2003). For example, what is the most appropriate length of climate records that need to be taken into account to assess current frost risk? Too long a period will result in inefficiencies whilst decisions based on only the last few years include the risk arising from assumptions that the trend will continue. Identification and quantification of appropriate strategies require a clear understanding of the nature and magnitude of such climatic trends and a quantitative understanding of their impact on production and NRM issues. Due to the long timeframe involved over which such climate trends manifest themselves (decades rather than years), our current practices are to some extent 'self-adapting', whereby producers and policy makers modify their behaviour based on most recent experiences (Meinke and Stone, 2003). The masking effect of variability, however, means that such subconscious self-adaptation is haphazard, non-specific and often involves considerable lag periods.

The Emerald region in Central Queensland is at the most northerly margin where winter cropping occurs in Australia. Any impact of possible climate change is likely to manifest itself first in such marginal environments (Howden et al., 2001). As part of a larger study being undertaken for Land and Water Australia that examines the impact of climatic trends on the cropping and pasture industries of Northern Australia, we examine in this paper the impact of changes in minimum temperatures on the performance of wheat in the Emerald region.

Specifically, the risks and economic value of various management rules (strategies) were quantified. This approach allows a comparative assessment of different strategies that either take trends in frost risk into account or maintain a conservative stance that ignores those trends.

2. MATERIAL AND METHODS

Using historical, daily climate records from 1894 to 2002 for Emerald, Central Queensland (23.5^{o}S, 148^{o}E), trend analyses of changes in mean and extreme temperatures during the last century were conducted. In order to assess the impact of these trends on wheat crops and their management, simulation studies using APSIM-Wheat (Keating et al., 2003) were also conducted.

To quantify frost risk for a wheat crop, sequential fortnightly sowings (1 April to 15 July) of two wheat maturity types (an early maturing type similar to the variety 'Hartog' and a later maturing type similar to the variety 'Cunningham') were simulated for the 109 years of climate records and the corresponding modelled anthesis date recorded. The frost sensitive period was assumed to last from anthesis to the end of grainfilling (Woodruff and Tonks, 1983). From the long-term climate records, frost risk probabilities for a range of screen temperatures (+2^{o}C to –2^{o}C) were calculated (Goyne et al., 1996). These calculations were based either on (a) the entire 109-year temperature record or (b) independently for each decade during the 20th century.

Wheat simulations were conducted based on typical agronomic and soil conditions in the Emerald region. For the purpose of this study, only the early maturing wheat variety was considered and it was assumed that nitrogen did not limit production. 'Frost risk' was defined as any day on which the minimum recorded screen temperature fell below 2^{o}C at or after anthesis: a conservative indicator which takes into account potential local topography ('frost pockets') that can increase frost risk (Hammer and Rosenthal 1978). Whenever such a 'frost event' occurred, simulated wheat yields were assumed to be zero.

In this environment, early-planted wheat runs the risk of frost damage during or after anthesis, while late-planted wheat can suffer from water limitations and high temperatures during grainfilling. Woodruff and Tonks (1983) reported a near linear decline of 1.2% d^{-1} for Queensland wheat yields as flowering date departed from the mid winter period. Doyle and Marcellos (1974) reported declines in relative grain yields of wheat of 5 to 7% for each week planting was delayed after the end of June in northern NSW. Thus, good, quantitative information is essential to manage the delicate balance between frost risk and declining yield potential.

For the evaluation of frost risk management strategies, we assumed a wheat – fallow – wheat monoculture. The soil profile was assumed to hold 80% of the total plant available water holding capacity on 1 April.

Three management strategies were:

(a) *frost risk benchmark:* frost risk was ignored and wheat planted whenever a planting opportunity (defined as a minimum of 10mm rain over 3 days) occurred between 1 April and 15 July;

(b) *conservative strategy:* the planting window was restricted to the time period that corresponded to 10% or less frost risk at or after anthesis based on the occurrence of a 2^{o}C screen temperature or lower using the entire 109-year temperature record;

(c) *adaptive strategy:* as (b) but frost risk probabilities were calculated based on the preceding decade and the opening of the planting window altered accordingly for each decade (incremented on a one year basis).

Strategies were evaluated in terms of production (wheat yields) and gross margin distributions. For the economic analysis costs and prices were assumed to be constant and in line with recent experiences in the region. This is appropriate in order to assess the impact of climate variability on current production. In years when no planting rain occurred (missed plantings) or frost was recorded at or after anthesis, all yields were assumed to be zero. A missed planting incurred losses of \$35 ha^{-1}; years when wheat was planted but affected by frost incurred losses of $120 ha^{-1} and years when a crop was planted and harvested incurred variable costs of $140 ha^{-1}. The wheat price (prime hard wheat) was assumed to be $240 t^{-1}. This implied that a minimum yield of 0.58 t ha^{-1} was required to recoup variable costs ('break-even-yield').

3. RESULTS AND DISCUSSION

3.1 Temperature trends during the 20th century at Emerald

According to Australia-wide analyses, there has been a sustained increase in continent-wide temperatures since 1950 with the rises greatest over the north-eastern interior (e.g. Collins et al., 2000; Meinke et al., 2003). The rises have been greatest in minimum temperatures (an increase of 1.0ºC between 1950 and 2001); smaller increases have occurred in maximum temperatures over that period (0.6ºC). The 1990s were the warmest decade since records commenced in 1910, and the 1980s the second warmest. Similarly, frost frequencies and the duration of the frost period, particularly over Queensland and northern NSW, have decreased markedly since 1970 (Stone et al., 1996). This has coincided with a change to earlier sowing of wheat and an increase in wheat yields.

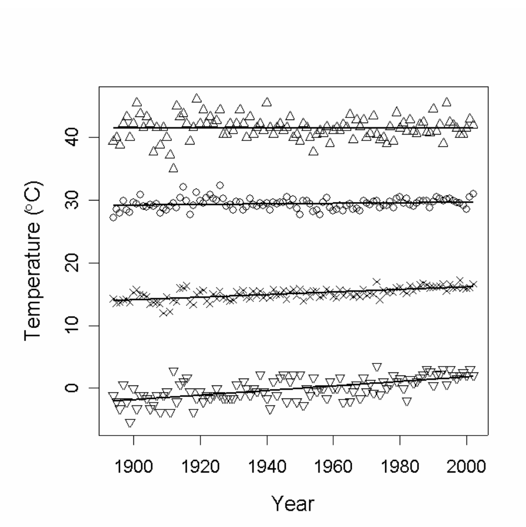

Figure 1. Mean annual maximum (o) and minimum (x) temperatures and annual extreme maximum (Δ) and minimum (□) temperatures recorded at Emerald between 1894 and 2002.

Trends at one climatological recording station (Emerald) were analysed. This indicated that at Emerald mean annual maximum temperatures have increased by 0.4 degrees from 29.3^{o}C in 1900 to 29.7^{o}C in 2000. Over the same period, mean annual minimum temperatures have increased by 2.1 degrees from 14.0^{o}C to 16.1^{o}C (Fig. 1). This is in line with reports by Collins et al. (2000) and Stone et al. (1996). It is also consistent with global trends as reported by the IPCC (2001).

A more detailed examination of the data revealed no changes in the extremes of annual, maximum temperatures, in spite of a slight increase in the mean annual temperature (Fig. 1). This implies that while the frequency of above-median temperatures has increased during the last century, the absolute values of extreme maximum temperatures have not.

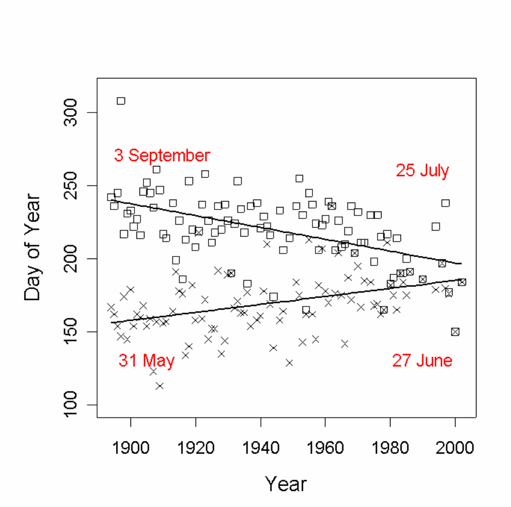

Figure 2. Changes in the dates of first (x) and last (□) frost at Emerald during the last century (expressed as a screen temperature of 2^{o}C or lower).

However, a strong trend exists in the extreme minimum temperatures, with the lowest annually recorded temperature rising from about –1.9 in 1900 to about +1.8 in 2000 (Fig. 1). We observed no such trend for the highest annual minimum temperature. Again, this is in accordance with Collins et al. (2000), who reported increases in minimum temperatures chiefly in the period autumn through spring.

Fig. 2 shows that the average frost risk period has been reduced from approximately 80 days at the end of the 19th century (3 June to 24 August for 1900) to about 17 days today (29 June to 16 July for 2000). In 1978, Hammer and Rosenthal reported a median frost window for the same location and a 2^{o}C screen temperature of 10 June to 17 August. Today, wheat in this region is sown earlier than in the 1950s and 60s, targeting flowering dates of early to mid August. Maturity types have been adapted accordingly. Thus, when and where there is adequate moisture there is likely to be advantage in breeding and adopting slower-maturing cultivars that can capitalise on the earlier date of flowering and longer photosyntheticallyactive periods before seasonal water limitations force maturity.

3.2 Evaluation of planting strategies

As a rule of thumb, many farmers regard a '1 in 10' frost event as an unavoidable hazard and target their variety choices and planting dates accordingly e.g. Hammer and Rosenthal 1978). Diversifications in terms of planting multiple maturity types, staggering planting dates and paddock selections based on topography can further mitigate impacts of such '1 in 10' events.

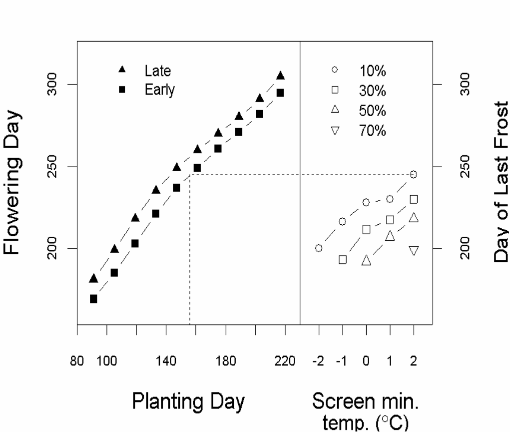

Figure 3. *Left:* Simulated flowering dates as a function of planting date (1 April = day 90; 31 July = day 212) for an early (e.g. cv 'Hartog') and a late (e.g. cv 'Cunningham') maturing wheat variety at Emerald. *Right:* Corresponding frost probabilities, based on the entire temperature record for the 20th century, for a range of screen temperatures (2°C to –2°C) expressed as the probability of falling below a specified temperature threshold after a certain date ('day of last frost'). The dashed line indicates the planting date for an early maturing wheat variety that corresponds to a 10% frost risk probability based on a screen temperature of 2°C. This indicates that any planting date after 6 June would have 10% or less risk of such a minimum temperature occurring.

Based on simulated wheat ontogeny, Fig. 3 provides quantitative information that allows users to determine the most appropriate planting date for a given wheat maturity type and level of frost risk. The example (dotted line, Fig. 3) shows that an early maturing wheat cultivar sown on 6 June would flower on 1 September. Based on the analysis of the 109 years of temperature data available for this location and without taking climate trends into account (i.e. the 'conservative' strategy B), there is a 10% chance of receiving a 2°C screen temperature on or after that date. Such analyses have been conducted before (e.g. Hammer and Rosenthal, 1978; Goyne et al., 1996), but can result in over-conservative estimates of frost risks because temperature trends have not been accounted for. The strong decline in frost risk (Fig. 2) during the last century raises the question: what would be the long-term economic consequence of an 'adaptive strategy', whereby planting decisions (sowing windows) are based on climatic records from the preceding decade and continuously adjusted with time? An attempt to answer this question was made by simulating the three different management strategies described earlier A) 'benchmark, B) conservative and C) adaptive. Hence, we quantified the 10-percentile frost risk for each decade (for clarity only 20-year periods are presented in Fig. 4).

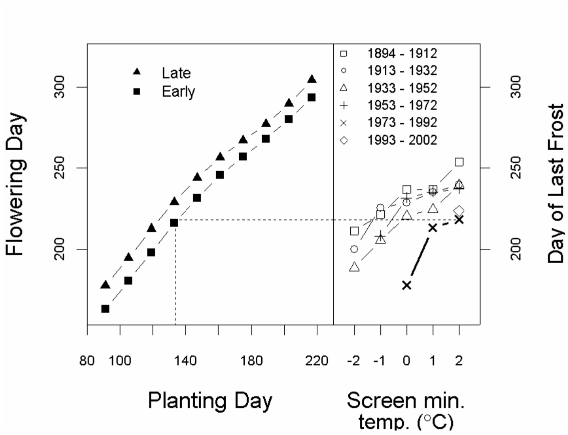

Figure 4. *Left*: as in Fig. 3; *Right:* As in Fig. 3 but for the 10-percentile frost risk for different 20-year periods from 1884 to 2002.

In these simulations, two types of crop failure can occur: a crop can either suffer from frost damage (in which case we assumed a total crop loss), or insufficient rainfall might result in a missed planting opportunity for that year. While the economic consequences of these different types of failure differ (see later), they both result in zero yields for that year. Summary statistics regarding the performance of these strategies are presented in Table 1.

The probabilities of exceeding given yield and gross margin levels demonstrated the trade-offs between frost risk and yield potential (Table 1 and Fig. 5 and 6): Under management strategy 'A' about 56% of all years resulted in crop failures due to frost and another 6% experienced missed planting opportunities. However, in the remaining 38% of years, simulated crop yields mostly exceeded the yields of the other strategies with an average yield of 1.8 t ha^{-1}.

This was in stark contrast to the conservative strategy (B), where frost damage was practically eliminated (less than 4% of all years were frost affected in spite of the '10% rule' for frost – this is due to the fact that a planting rain is still required after the sowing window commences). The late opening of the sowing window (5 June instead of 1 April for strategy 'A') meant that not many planting opportunities occurred within this short period, resulting in missed plantings in 34% of years. Even in years when a 'strategy B' wheat crop was harvested, yields were low (average of harvested yield = 0.89 t ha^{-1}, Table 1) due to hot and dry conditions during grainfilling.

Strategy	A	B	C
Start of Planting Window	01-Apr	05-June	Min 24-April Max 12-June Med 28–May
Mean / median planting date	26-Apr 20-Apr	19-June 16-June	04-June 02-June
Number of frosts	61 (of 100)	4 (of 72)	6 (of 71)
Number of years without planting opportunity	9	37	30
*Mean / median **total** yield (t ha^{-1})*	0.64/0	0.55/0.45	0.66/0.55
*Mean / median **harvested** yield (t ha^{1})*	1.82/1.51	0.89/0.63	1.03/0.83
*Mean / median **total** gross margin ($ ha^{-1})*	34/-120	29/-32	52/-8
*Mean / median **harvested** gross margin ($ ha^{-1})*	291/216	54/13	92/38

Table 1: Summary statistics for the management strategies based on the planting rules (i.e. 10mm of rain received over 3 days or less and a maximum of 10% frost risk; strategies B and C only).

Strategy 'C' represented an adaptive response whereby planting decisions were based on the previous 10 years of climate records, essentially incorporating the changes observed in frost risk into the planting decisions. This resulted in a shift of 7 weeks in planting dates from 12 June in early 1900 to 24 April today. Although the number of failed crops due to frost was marginally higher than for the conservative strategy, this was compensated for by more crops planted and the fact that many more crops matured earlier during climatic conditions that were conducive to higher yields. This is reflected in the economic performance, where strategy B averaged $54 and strategy C $92 for all harvested crops (Table 1; Fig 5 and 6).

This study highlighted the value of management adaptation to changes in climatic conditions. Here we have concentrated solely on the evaluation of temperature trends. We have considered neither changes in the amount or variability of rainfall (although these effects are intrinsic to the simulation results that were obtained by using a 109-year climate record), nor have we considered benefits that might occur from increased transpiration efficiency as a consequence of CO_2 fertilisation (Howden et al., 1999). Similarly, we have not incorporated changes to maturity types in conjunction with the adaptation of planting windows: likely to enhance the benefits from the adaptative strategy. We will consider such issues as part of a more comprehensive research project.

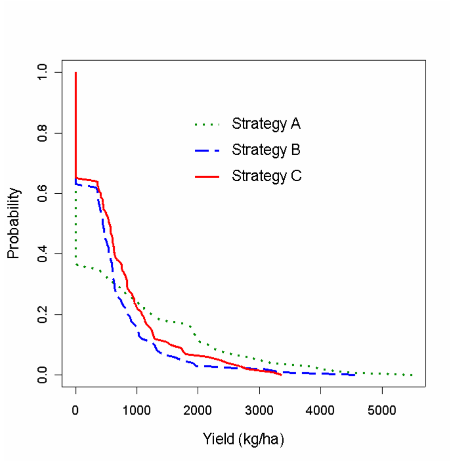

Figure 5. Cumulative probabilities of wheat yields (see Table 1 for details).

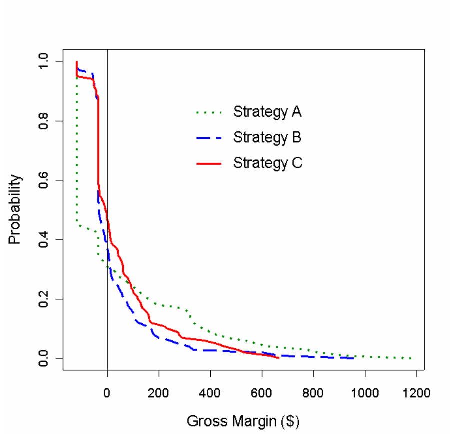

Figure 6. Cumulative probabilities for gross margins (see Table 1 for details).

4. CONCLUSIONS

Here we have shown that the warming trend observed for Emerald (CQ) during the last century was nearly entirely due to increases in winter and spring minimum temperatures. As a consequence, the period during which wheat crops are at risk of being damaged by frost has reduced considerably. This has allowed producers to plant crops earlier so that crops can mature under milder conditions when environmental yield potentials are higher. Using simulation analysis we then demonstrated that basing decisions on 100+ year climate records without explicitly accounting for non-stationary trends can lead to over-conservative strategies that might have low risk of crop failure but are clearly under-performing economically. An adaptive strategy, whereby recent climate trends are explicitly accounted for, resulted in a clear economic advantage when compared to the 'benchmark' (i.e. frost risk ignored) or the conservative strategy. Anecdotal evidence suggests that current planting dates are similar to those obtained from the adaptive strategy, providing further evidence for an ongoing process of 'self-adaptation' as suggested by Meinke and Stone (2003).

The work demonstrated that (i) climate change, either natural or anthropogenic, is already likely to be impacting on agricultural production systems and their management, (ii) management tools, such as simulation modelling, that have traditionally been used for climate variability assessments can be used equally well to develop adaptive strategies to climatic change and (iii) active industry engagement and grower awareness will lead to a more timely and accurate information that will ultimately result in either lower production risk, better economic returns or both.

5. ACKNOWLEDGMENTS

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6. REFERENCES

Collins, D.A., P.M., Della-Marta, N. Plummer, and B.C.,Trewin, Trends in annual frequencies of extreme temperature events in Australia, *Australian Meteorological Magazine*, *49,* 277-292, 2000.

Doyle, A.D., and H. Marcellos, Time of sowing and wheat yield in northern *New South Wales, Australian Journal of Experimental Agriculture and Animal Husbandry, 14,* 93–102. 1974.

Hammer, G.L. and K.M. Rosenthal, Frost and minimum temperature probabilities, *Queensland Agricultural Journal*, March-April, 3-27, 1978.

Howden, S.M., P.J. Reyenga, and H. Meinke, Global Change Impacts on Australian Wheat Cropping, Report to the Australian Greenhouse Office, CSIRO Wildlife and Ecology Working Paper 99/04, 121 pp., Canberra, 1999.

Howden, S.M., G.M. McKeon, H. Meinke, M. Entel and N. Flood, Impacts of climate change and climate variability on the competitiveness of wheat and beef cattle production in Emerald, north-east Australia, *Environment International, 27,* 155-160, 2001.

Howden, S.M., A.J. Ash, E.W.R. Barlow, T. Booth, S. Charles, R. Cechet, S. Crimp, R.M. Gifford, K. Hennessy, R.N. Jones, M.U.F. Kirschbaum, G.M. McKeon, H. Meinke, S. Park, R. Sutherst, L. Webb, and P.J. Whetton, An overview of the adaptive capacity of the Australian agricultural sector to climate change – options, costs and benefits, Report to the Australian Greenhouse Office, 157 pp., Canberra, Australia, 2003.

IPCC 2001. Third Assessment Report – Climate Change, Cambridge University Press, Cambridge, UK, (http://www.ipcc.ch), 2001

Keating, B.A., P.S. Carberry, G.L. Hammer, M.E. Probert, M.J. Robertson, D. Holzworth, N.I. Huth, J.N.G. Hargreaves, H. Meinke, Z. Hochman, G. McLean, K. Verburg, V. Snow, J.P. Dimes, M. Silburn, E. Wang, S. Brown, K.L. Bristow, S. Asseng, S. Chapman, R.L. McCown, D.M. Freebairn, and C.J. Smith, An overview of APSIM, a model designed for farming systems simulation, *European Journal of Agronomy*, *18,* 267-288, 2003.

Meinke, H. and R.C. Stone, Seasonal and inter-annual climate forecasting: the new tool for increasing preparedness to climate variability and change in agricultural planning and operations. *Climatic Change*, in press, 2003.

Meinke, H., W. Wright, P. Hayman, and D. Stephens, Managing cropping systems in variable climates, In Pratley, J. (editor). Principles of field crop production, Fourth Edition, Oxford University Press, Melbourne, Australia, 26-77, 2003.

Stone, R.C., N. Nicholls and G.L. Hammer, Frost in NE Australia: trends and influences of phases of the Southern Oscillation*, Journal of Climate*, *9,* 1896-1909, 1996.

Suppiah, R. and K.J. Hennessy, Trends in total rainfall, heavy rain events and number of dry days in Australia, 1910-1990, *International Journal of Climatology*, *18*, 1141-1164, 1998.

Woodruff, D.R. and J. Tonks, Relationship between time of anthesis and grain yield of wheat genotypes with differing developmental patterns, *Australian Journal of Agricultural Research*, *34*, 1–11, 1983.