EVALUATING HEAT STRESS IN AUSTRALIAN WHEAT

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Declaration of Originality

This thesis reports the original work of the author, except as otherwise stated. It has not been submitted previously for a degree at this or any other university.

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Abstract

Bread wheat in Australia is generally grown as a winter crop. Sowing time is important as the flowering stage needs to be timed so as to be after the last frost, but the grain development stage needs to occur before the onset of potentially damaging high summer temperatures. Many wheat growing areas in Australia are already subject to episodes of higher than optimal temperatures during the normal reproductive and grain filling stages. The advent of climate change in Australia is forecast to produce a hotter and drier climate, with less reliable rainfall. It will be important for wheat farmers to understand not only the likely timing and effects of heat episodes, but also which wheat varieties are best suited for their area and climate. The central research question of this study therefore was: to what extent do episodes of above average temperatures affect wheat yields? The related research question was: are selected overseas research genotypes more heat tolerant than local varieties?

Statistical models (such as time series) and ecophysiological models (such as APSIM) are two of the main types used to predict the performance of crops such as wheat. Time series modelling can help elucidate the relationship between historical wheat yields and weather variables. This approach can be useful when there is a sufficiently long period of yield and weather variable datasets available. In Australia, there is a close relationship between above average temperatures and drought. For the first study the initial aim was to identify and quantify the relationship between yield, higher temperatures and growing season rainfall in an area of southern NSW. The hypothesis was that the high temperature/rainfall relationship can be separated and quantified, using statistical modelling, and validated against the predictions of the APSIM simulations. The next aim was to determine if past wheat yields have been negatively affected by heat episodes. The hypothesis was that yield reductions do regularly occur as a result of above optimal temperatures during the reproductive stages of wheat crops in Australia. For this purpose a combination of statistical (time series) and ecophysiological (APSIM) modelling was used. The final aim in this part of the study was to compare the time series and the APSIM predictions with each other and with observed yields, using the same weather station records. The hypothesis was that APSIM does not correctly model the effects of heat stress during the reproductive stages. The area studied comprised of six shires in southern NSW which together formed a large part of Statistical Division 150 (SD150). The times series study was done by building a series of regression models using historical weather records (1922-1994) and yields from the six shires in southern NSW. To measure above average heat, a derived weather variable, high degree hours (HDH), was calculated for each season. HDH is a measure of the number of hours that temperatures are above optimal values during the reproductive stages of the wheat crop. The effects of rainfall and HDH on wheat yields could be separated and quantified provided the areas being analysed have similar weather patterns and soil qualities. Growing season rainfall in southern NSW has a positive effect on wheat yields while high temperatures have a negative effect. 3D plots of yield versus growing season rainfall and HDH indicate that HDH has the most noticeable negative effect within a rainfall band of 15-45% below average. In the warmer/drier north western shires there was an average 15% yield reduction over the study period due to HDH. Over the whole area there was an average 8.4% yield reduction when rainfall is 10% below average, and a 5.3% yield reduction for each 1°C rise in average growing season temperature. When the time series model predictions and the APSIM simulation predictions were validated against a later set (1982-2008) of weather data and observed yield records from SD150, the predictions of the time series model were superior. Validation regressions for the time series model were: slope=0.95, R^2=0.82, RMSE=14.6, while for APSIM the validation regressions were: slope=0.84, R^2=0.69, RMSE=18.9. Disentangling rainfall and temperature effects using statistical modelling is challenging due to the co-linearity of many of the environmental factors, including rainfall and temperature. Another consideration was the non-linearity of rainfall effects; when rainfall is above 30% of the season average, the yield response plateaus and then becomes negative. Other experimental setups in Australia have largely used APSIM as a predictive tool for wheat yields. The statistical model built and validated in this study performed better than APSIM, but the yield predictions of the two methods were reasonably similar. The statistical model predicted higher yield losses than APSIM in seasons of high HDH, but this may reflect the fact that APSIM does not model correctly the damaging effects of HDH during the reproductive stages of wheat crops. The conclusion was that statistical modelling is a useful tool that can separate and quantify the effects of rainfall and high

temperatures when applied to smaller and relatively environmentally homogeneous wheat cropping areas.

It would be useful if simulation models could accurately model the effects of changed climate on wheat crop yields. However, there is a degree of uncertainty if predictions use climate scenarios that have weather variable ranges beyond those that have previously been used for model fitting and validation. Yield responses are rarely linear over the range of temperatures and seasonal rainfall that are historically encountered. Thus, predictions should ideally be only attempted for the near future, within the range of weather variables values that have already been encountered. An alternative is to use two simulation model types and compare their predictions. The aim of the second study therefore, was to compare the yield predictions of the time series and the APSIM models when there is a simulated 1°C rise in average growing season temperature and/or a 10% reduction in growing season rainfall. The hypothesis was that the time series model would be more sensitive to high degree hours (HDH) than APSIM. Actual weather stations records for the period 1922-2008 were used, but adjusted to reflect the average 1˚C temperature rise and/or a 10% reduction in growing season rainfall. For the time series model the historic daily growing season temperatures were increased by 1°C and the growing season daily rainfall reduced by 10%. For APSIM the 'climate control' option was used to specify a constant +1°C daily for minimum and maximum temperatures and -10% for daily rainfall. The average percentage yield changes (with coefficient of correlation) for the respective time series/APSIM model forecasts for a 1˚C rise in average temperature were: -5.3%/-4.0% (0.72), for a 10% reduction in growing season rainfall: -7.1%/-9.9% (0.82), and for a combined 1˚C average temperature rise and 10% reduction in rainfall: -12.4%/-13.7% (0.83). Overall, across the shires, APSIM predicted higher yield reductions for the 10% rainfall reduction than the time series model, while for the 1°C temperature rise the time series model predicted the higher yield reductions. Higher yield reductions were predicted for all scenarios in the hotter and drier north western shires compared to the cooler and wetter south eastern shires. An analysis of the APSIM predicted yields versus high degree hours (HDH), i.e. threshold temperatures above which damage to reproductive mechanisms may occur indicated that APSIM (7.5) did not directly model the effects of HDH. The time series and the APSIM model produced similar outputs overall, but across all shires, the time series model consistently predicted higher yield losses for increased

HDH than APSIM while APSIM predicted higher losses for decreased rainfall. Field experiments with controlled temperature and rainfall changes may be a way to find out which model has the correct emphasis.

Identifying the extent to which wheat crops in southern NSW have suffered yield losses due to heat episodes, particularly during the reproductive stages, is a step forward, but does not resolve the problem. As the yield losses are likely to become more severe, as indicated by climate change predictions, new cropping strategies need to be considered. A range of options include: growing different crops, relocating to new areas, better soil water management and/or using irrigation. If the option is to continue growing wheat then part of the solution is to develop new wheat varieties that are more tolerant of heat. Wheat genotypes have been developed overseas for improved heat tolerance, but they need to be compared with locally grown varieties in a range of growing environments to assess and characterise their likely yield performance in target environments in Australia. The aim of this study was to establish if selected overseas research genotypes were more heat tolerant than selected Australian varieties and whether there is a consistent relationship between the heat tolerances of genotypes across different experimental setups and environments. The hypothesis was that the research genotypes would show improved heat tolerance in all the experimental environments. Experiments were conducted in the field at Narrabri in 2011 and 2012 and at the University of Sydney greenhouse at Darlington in 2011. The greenhouse experiment subjected the selected genotypes (local: CRUSADER, BERKUT, EGA GREGORY, LIVINGSTON, overseas: PBW343, WH 542, SOKOLL, N-ABYAD-13, ZAKIA-10, FILIN) to heat stress (38°C) for four days at anthesis. The same genotypes were used in field experiments which were conducted at Narrabri in 2011 and 2012, using normal and late sowing dates, to subject the late sown varieties to heat stress. A heat stress index was used to compare the performance of varieties. The data were variable across the experimental environments (greenhouse and field) and years (2011 and 2012). The greenhouse data indicated one locally grown variety (CRUSADER) and three overseas genotypes (PBW343, WH 542 and SOKOLL) had superior heat tolerance. The 2011 Narrabri field experiment had a normal and late planting date but the late planting date encountered relatively cooler temperatures. The data indicated CRUSADER, PB343 and FILIN had relatively higher grain yield under high temperature conditions. In 2012 there were three planting dates with the third experiencing considerably higher temperatures than the other field experiments. Again the locally grown CRUSADER performed well in the second planting date but not so well in the later and hotter third planting date. PBW343, SOKOLL and N-ABYAD-10 and ZAKIA-10 were the best performers overall under high temperatures in the 2012 Narrabri experiment. The greenhouse experiments, which applied heat only at anthesis, had a larger drop in grain number than the Narrabri field experiments. In the Narrabri experiments yield loss was mainly due to reduction in thousand kernel weight. The conclusion was that the timing of heat stress is an important consideration. The high degree of heat applied at anthesis in the greenhouse experiments indicate the yield loss in this case was due to pollen or fertilization mechanism damage. In the field experiments the damage more likely occurred during grain filling. The decision as to which varieties are superior depends on the type and degree of heat tolerance been targeted in the breeding program. Overseas genotypes were generally higher yielding under higher temperatures in these experiments, but there was a significant genotype x environment interaction and more experiments in target environments are required to reach a conclusion as to which genotypes are superior performers.

Table of Contents

List of Tables

List of Figures

Abbreviations

Abbreviation	Term Represented
APSIM	The Agricultural Production Systems sIMulator
BOM	Australian Bureau of Meteorology
HDH	High Degree Hours
NSW	New South Wales
QLD	Queensland
SA	South Australia
SD	Statistical Division
WA	Western Australia
Wagga	Wagga Wagga

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Chapter 1 - Introduction

1.1 Background

Wheat growing areas in Australia extend from south eastern Queensland through NSW, Victoria, the southern parts South Australia and the south west of Western Australia (Figure 1-1). Wheat in Australia can be broadly separated into types grown for noodles (Durum) and those grown primarily for bread making. This thesis concentrates on the effects of heat on wheat crops in southern NSW where the predominant wheat crop types are Australian premium and Australia hard which are mainly used for bread making.

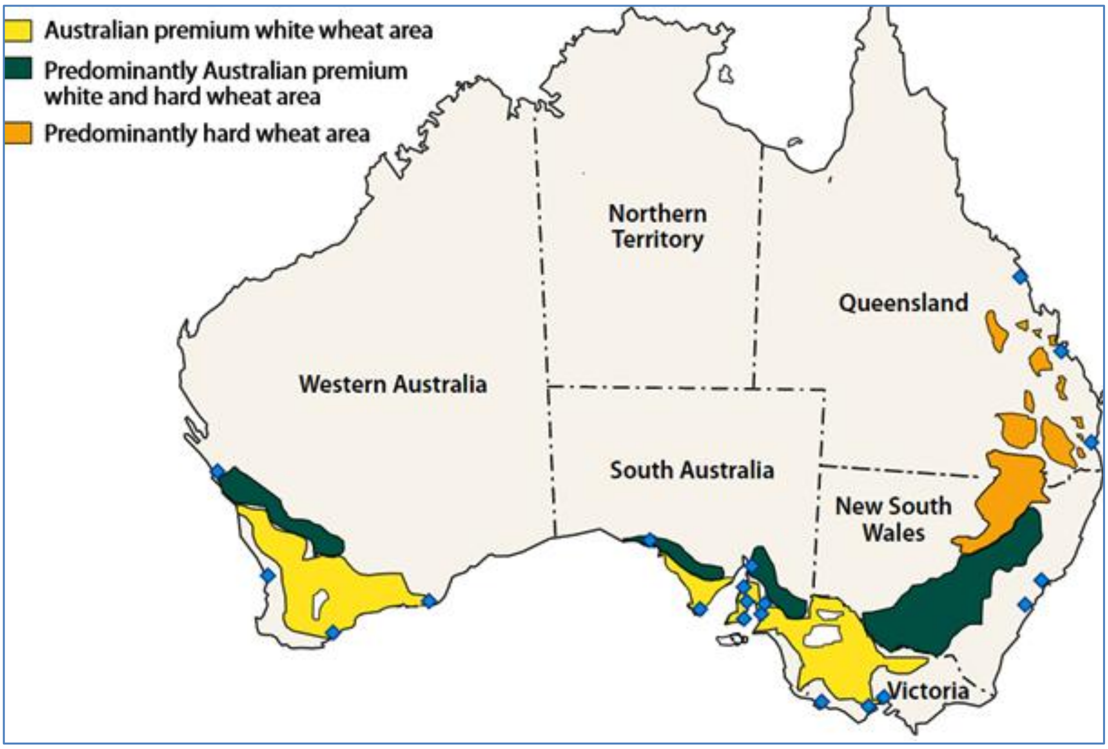


Figure 1-1. Australian wheat growing regions and wheat types (ABARE, 2010).

In 2011 WA was Australia's largest wheat producing state (34%) followed by NSW (30%). A major portion of the NSW wheat crop is produced in southern NSW (Figure 1-2). Most Australian wheat is grown as a winter crop with plantings approximately mid-April to early July and harvesting October to early January. The sowing and harvest dates for the southern most areas of Australia can be later by one month or more than the northern region harvest dates. Rainfall in the northern areas, such as Queensland, is more predominantly in summer, in southern NSW rainfall is more evenly distributed through the year while Victoria and WA have a more winter dominant rainfall pattern.

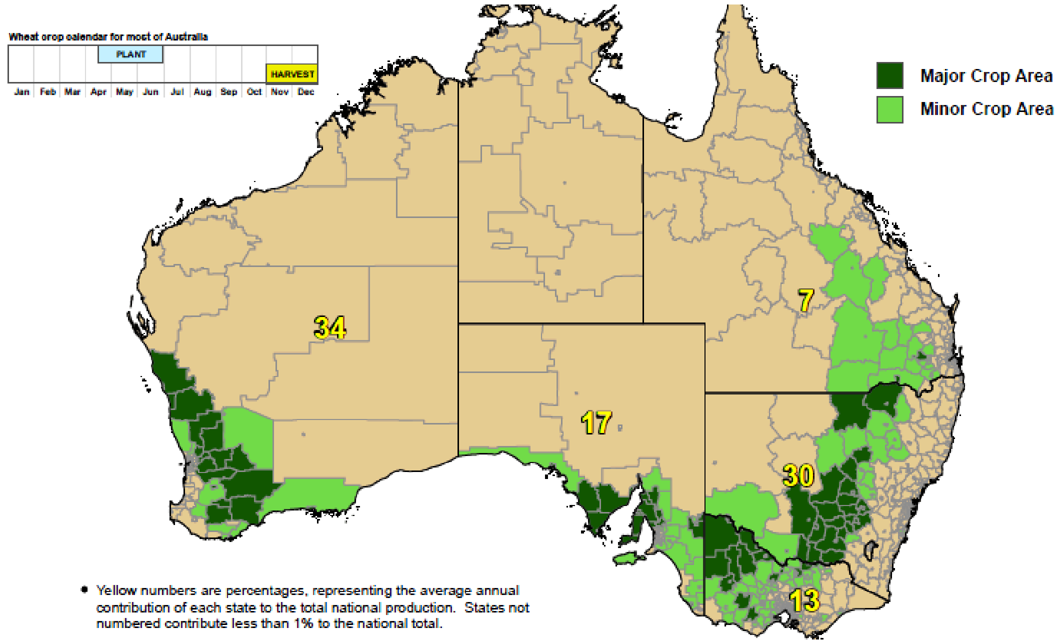
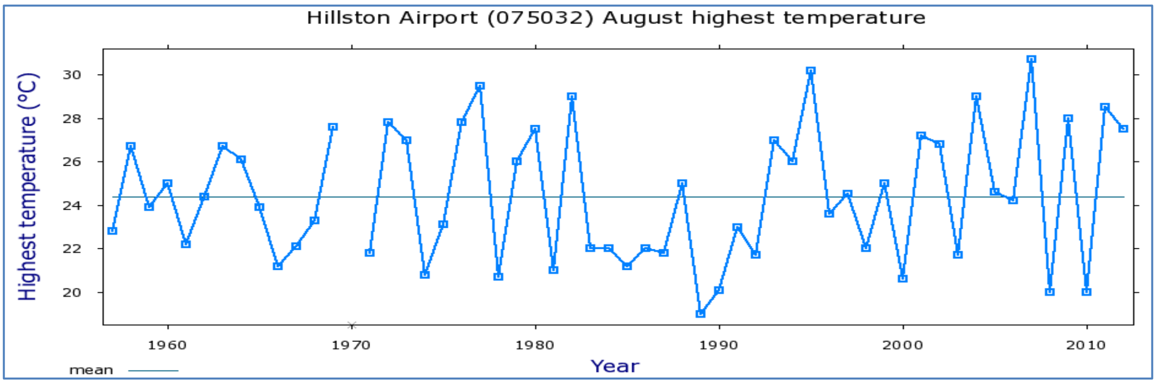


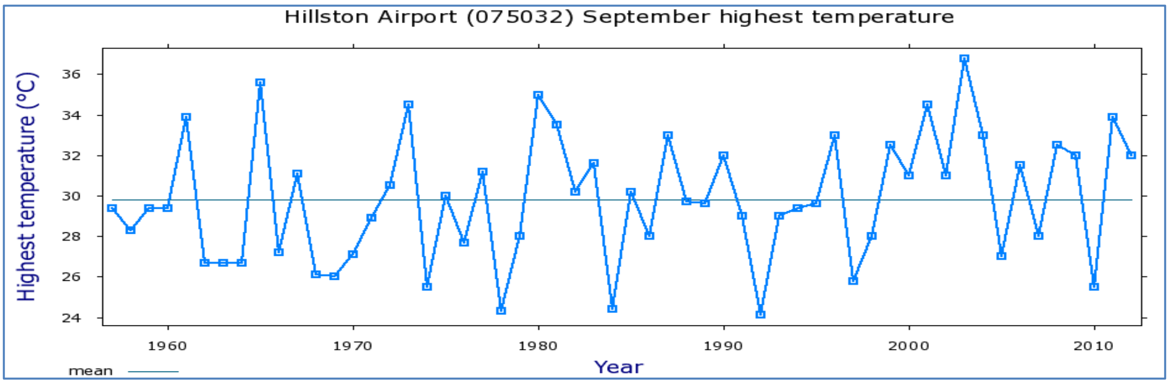
Figure 1-2. Percentage of total Australian wheat production by state in 2011 (USDA, 2011).

1.1.1 Climate constraints

The successful production of a wheat crop in Australia is influenced by many factors, such as climate, location, management and soils. Both timing of sowing and wheat variety choice have an important bearing on the final yield of the crop. In areas, such as southern NSW, sowing has to be late enough such that the reproductive stage is not subject to frost damage, but at the same time early enough so that hot weather does not damage the crop during reproductive and grain filling stages. Avoiding temperature stress is largely a matter of not only forecasting the coming season correctly, but also choosing the right wheat variety, for example a long or short season variety. The aim is to choose a variety and sowing time that maximises the probability of the maturation stage falling within the low frost risk and low heat risk window of ensuing spring and early summer.

Many areas of Australia, including southern NSW, already are subject to episodes of high temperatures during what would normally be the reproductive and grain filling stage of the currently sown wheat crops. The reproductive stage of most winter grown wheat varieties currently occurs in the August to September time frame. The reproductive stage is considered the weakest link in the susceptibility of wheat to high temperatures (Porter and Semenov, 2005; Saini and Aspinall, 1982; Zinn *et al.*, 2010). Farooq *et al.* (2011) reviewed the published literature on the level of temperature elevation that has experimentally been found to reduce wheat yields during the reproductive and grain filling stages. Critical temperatures were 21.4±2.3°C during the terminal spikelet stage, 32±1.7°C during anthesis and 34.3±2.7°C during the grain filling stage. For southern NSW the terminal spikelet stage occurs approximately during August, anthesis during September and grain filling during October. The critical temperature in each stage temperatures have been exceeded in many occasions in the south western NSW shire of Carrathool (Hillston Airport, Figure 1-3) and to a lesser extent in the more easterly shire of Wagga Wagga (Figure 1-3).





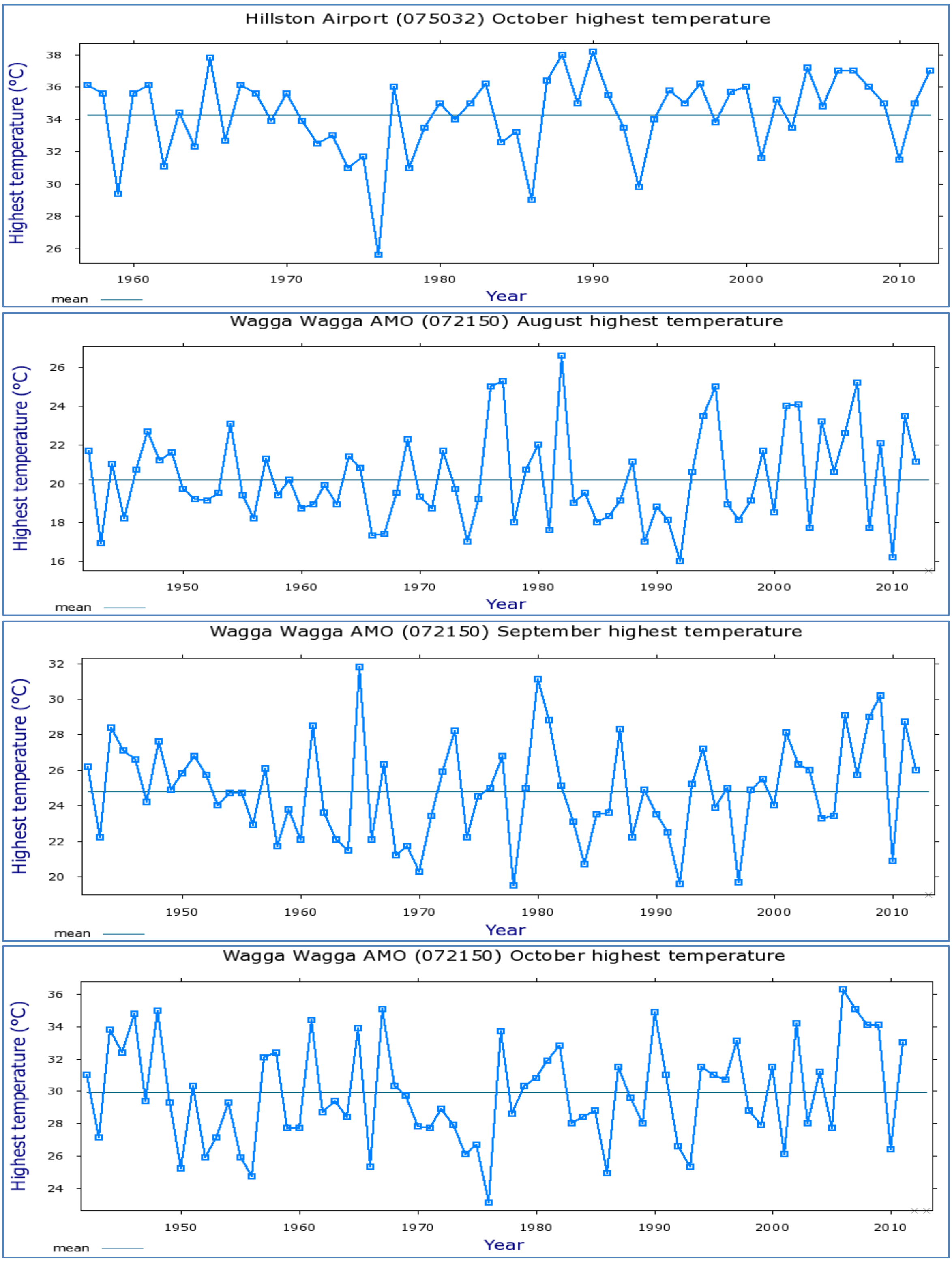


Figure 1-3. Maximum August, September and October temperatures for Hillston in the Carrathool shire of south western NSW (top) and Wagga Wagga in the Wagga Wagga shire of south eastern NSW. Future climates (BOM, 2011).

Thus current growing season temperatures already indicate the possibility of damage to wheat crops due to heat stress in southern NSW. This may be exacerbated in future years by climate change. The Australian Bureau of Meteorology (BOM) expects Australia's climate to become warmer and drier (BOM, 2007). By 2030 there could be an approximately 1ºC rise in annual average temperatures and an 7-10% decrease in combined winter and spring rainfall in inland NSW, relative to the period 1980-1999 (BOM, 2007). There will also be an increase in the number of days exceeding 35 ºC and 40ºC in the spring and summer months (Tebaldi and Knutti, 2010).

1.2 Central research questions

- Do heat episodes affect wheat yields in NSW and to what extent?
- Are selected overseas research genotypes more heat tolerant than local varieties?

1.3 Specific aims

- Identify and quantify the relationship between heat, rainfall and wheat yields in southern NSW using time series modelling;
- Compare APSIM and time series yield predictions using the same weather records and wheat cropping areas;
- Conduct greenhouse experiments to help determine the effect of high temperature during the reproductive stage on selected local and overseas wheat varieties; and
- Conduct field experiments over two years using normal and late sowing to help determine the relative heat tolerance of selected local and overseas wheat varieties.

Chapter 2 – Literature Review

2.1 Review introduction

This review surveys the past and current climatic conditions that affect wheat growing in Australia. Relevant literature covering research into heat stress on plants in general is then examined. The effects of heat stress on the growth stages of cereal crops such as wheat are reviewed, with research covering the effects of heat stress on the reproductive stage being looked at in particular, as this has been proposed as the weakest link (Zinn *et al.*, 2010). Some of the general literature on the simulation modelling of crops is then reviewed, including statistical and ecophysiological models. The availability of both Australian climatic and wheat yield datasets, and their completeness and quality, is also investigated. The literature detailing results and evaluations of higher temperature scenarios in Australia and the implications for Australian wheat cropping are then reviewed. Finally the use and validation of APSIM in Australia is reviewed; how it simulates high temperature stress, the relation of its methodology to other literature on heat stress modelling, and how if necessary APSIM could be modified and tested.

2.1.1 Climate and bread wheat in Australia

In Australia, bread wheat (*Tritcum aestivum)* is generally grown as a winter crop. Sowing time is important as the flowering should be after the last frost, but the grain filling period should occur before the onset of stressful high-temperature periods in summer. As a result of ongoing climate change, Australia's climate is expected to become warmer and drier. By mid-century temperatures on average in Southern Australia are projected to be 2.6ºC higher based on the Intergovernmental Panel on Climate Change (IPCC) A1B business as usual scenario (Solomon *et al.*, 2007; Tebaldi and Knutti, 2010). There will also be an increase in the number of days exceeding 35 ºC and 40ºC in the spring and summer months (Tebaldi and Knutti, 2010). Earlier studies indicated that the average daily minimum temperature has risen almost twice as fast as the average daily maximum over the past century (Vose *et al.*, 2005). Later updated observations have shown day and night-time temperatures to have risen at similar rates but there is significant regional variability (Solomon *et al.*, 2007). However the occurrence of temperature extremes, especially high temperatures, are trending upward faster than the mean temperature rise

(Alexander *et al.*, 2007). Climatic variability is predicted to have a negative effect on wheat yield in areas of Australia, such as south-eastern Australia (Anwar *et al.*, 2007) and South Australia (Luo *et al.*, 2010). An increase in the number of days > 34ºC during grain filling is predicted to reduce wheat yields generally throughout the wheat growing areas in Australia (Asseng *et al.*, 2011).

Higher temperatures may have multiple effects on wheat cropping. A positive effect may be fewer frosts and this may enable earlier sowing, thus escaping some of the higher temperatures of spring and early summer. However, higher temperatures will also lead to accelerated plant growth development, reduced grain filling period (Sharma *et al.*, 2008), and consequently reduced yields (Anwar *et al.*, 2007). Higher temperatures may also lead to increased maintenance respiration resulting in decreased carbon assimilation and reduced yields (Chauhan *et al.*, 2011; Reynolds *et al.*, 2001). The reproductive stage of most winter grown wheat varieties currently occurs in the August to September time frame. The reproductive stage is considered the weakest link in the susceptibility of wheat to high temperatures (Porter and Semenov, 2005; Saini and Aspinall, 1982; Zinn *et al.*, 2010). High temperatures during the early reproductive stage can damage the reproductive processes, resulting in male and female sterility as well as damage to pollen tube growth and fertilisation. This causes subsequent reductions in grain number and grain yield. High temperatures post-anthesis have a more marked effect on grain weight (see Appendix A Table A-1) (Kaur and Behl, 2010; Larcher, 2003; Prasad *et al.*, 2008; Saini and Aspinall, 1982; Talukder *et al.*, 2010; Wardlaw *et al.*, 1989b). High temperatures resulting in negative effects at the reproductive stage of wheat development do already occur in the northern wheat growing areas of Australia; see Appendix B (Table A-2) for representative temperature statistics. The projected elevation of temperatures resulting from climate change will make this problem worse.

2.1.2 **Night-time temperatures**

High night-time temperatures are related to reduced yield in wheat (Lobell and Ortiz-Monasterio, 2007) and rice (Peng *et al.*, 2004; Ziska and Manalo, 1996), but the reasons for this are unclear. The reproductive stage has been implicated for rice (Ziska and Manalo, 1996). Prasad *et al* (2008) investigated the effect of night-time temperatures during the reproductive phase of wheat in an attempt to quantify its effects on yield and other traits. They applied a range of night-time temperatures, (14, 17, 20, 23ºC), from the booting stage until harvest. In general spikelet fertility, grain number and grain weight decreased linearly with increasing night-time temperature. Photosynthesis, grain filling duration and grain yield also decreased. An earlier study by Saini and Aspinall (1982) also applied high night-time temperature of 30ºC at six different reproductive stages (covering Zadok stages 40-69), but at the same time a daytime temperature of 30ºC was also applied. Thus it is not clear if the grain number and grain weight variations observed at each stage were as a result of the increased day or night temperature treatments.

2.1.3 **Datasets and modelling**

Crop records and climate datasets can only provide a limited view of the real extent of the effects of heat stress episodes on wheat yield and quality. Yield datasets tend to be averaged over multiple districts that encompass a range of soil types and other environmental variables, such as solar radiation, cloud cover and rainfall. Management regimes and cultivar types vary from field to field and farm to farm. Climate datasets are not always complete. Other yield related environmental variables, such as rainfall and average temperature, and the problem of co-linearity between yield related variables, makes it difficult to separate out the effects heat stress effects alone, although one possibility is to search for areas where there appears to be less co-linearity between variables (Lobell, 2010). A well validated crop growth simulation program is a useful way of proposing the effects of variables such as heat stress. It is possible to hold all other variables steady while varying the variable of interest, thus elucidating its effect. APSIM (Agricultural Production Systems sIMulator) (Keating *et al.*, 2003) has been validated extensively for a wide range of wheat crop production situations in Australia (Asseng *et al.*, 2002; Asseng *et al.*, 2011; Chenu *et al.*, 2011; Sadras and Monzon, 2006) and other countries (Asseng *et al.*, 2004; Chen *et al.*, 2010). APSIM therefore is a candidate for evaluating past and future scenarios for wheat cropping in Australia, and quantifying the effects of inter-annual variations in heat stress episodes. The possibility then exists to improve the performance of APSIM using plant physiology science from currently available scientific literature and the output of field and glasshouse wheat heat stress studies.

2.2 **Current and past temperature regimes for Australian wheat**

Temperature records for wheat cropping areas of Australia show that maximum values already range up into the stressful range above 30 ºC during critical periods of wheat crop development (BOM, 2011). Appendix B (Table A-2) shows sample weather station temperature records kept by the Australian Bureau of Meteorology (BOM). Temperatures have varied from -8.6ºC in winter in Gunnedah to 44.8ºC in November in Trangie, New South Wales (NSW) (BOM, 2011). A more critical period however, for winter grown wheat crops, is August to October in the Northern regions such as Queensland, Northern NSW, and Western Australia, and August to November in the more Southern regions of NSW, Victoria and South Australia. During these periods high-temperature stress can negatively affect the reproductive and/or grain filling stages with consequently lowered yields (Gibson and Paulsen, 1999; Zinn *et al.*, 2010). BOM statistics (Appendix B, Table A-2) indicate that temperatures greater than 37 ºC and up to 41ºC have occurred during September and October in NSW and Queensland. In Trangie, north western NSW, the mean number of days greater than 30ºC is one in September and five in October. The night-time minimums in the same period for wheat growing areas of north western NSW and Queensland can range from 22-26ºC, within the range where damage occurs according to Prasad *et al.*(2008). The temperatures range up to 30ºC in October south of Geraldton (Appendix B, Table A-2), but in wheat growing areas in parts of Queensland and north western NSW the 100 percentile range is up to 30-33ºC, or one in 100 days on average is over 30ºC in these regions in October, during the grain filling period.

Wardlaw and Wrigley (1994) observed that, in the warmer Australian wheat cropping areas, temperatures can frequently rise above 30ºC during the grain filling period, but can also reach as high as 40ºC during this same period. In Adelaide, in early October 2004, temperatures reached 37.4ºC. Some agronomists estimated subsequent wheat yield losses in the area to be as high as 50% (Alexander *et al.*, 2010). Heat shocks, or the occurrence of short (one to five day) periods of stressful high temperatures during grain filling, are already common in middle to low latitudes and will become more common with the progression of climate change (Fischer, 2011). High temperatures tend to be accompanied by hot dry winds and this further aggravates the damage caused by heat shock (Fischer, 2011). In a study of a cross section of wheat growing districts of Australia between 1958 and 2007, Asseng *et al.* (2011), found that there were on average 2.9 days with maximum temperature greater than 34ºC in Miles, Qld., during the grain filling period (Sep-Oct). In Cunderdin, W.A., for the grain filling period (Oct-Nov) this figure was 5.5 days. There was also a upward trend in days per decade of 0.66 and 0.36 for Miles and Cunderdin respectively (although the authors report the trends as not statistically significant). Appendix B, Figure A-1 gives an indication of the overall maximum temperature 100th percentiles for the August to September period in the wheat cropping areas of Australia.

2.3 **Experiment studies**

2.3.1 **Heat stress effects on plant structure and function**

Grant *et al.* (2011) identify five processes in crop production that are affected to varying extents by heat:

1. Transpiration increases and this hastens soil drying with subsequent declines in canopy water potentials, stomatal conductance, CO_2 fixation and crop growth.
2. At higher temperatures, photorespiration increases relative to carboxylation and hence less net CO_2 fixation.
3. Dark respiration increases and offsets gains from CO_2 fixation.
4. Phenological growth stages are shortened leading to less seasonal CO_2 fixation and crop growth.
5. Seed set is impaired at higher temperatures, leading to reduced seed numbers and yield.

Larcher (2003) identified three possible stages of stress in plants:

- Alarm phase - initial de-stabilisation of biochemical and metabolic functional processes and structures such as proteins, membranes and cytoskeleton.
- Resistance phase – or hardening, protective measures, synthesis of proteins and protective substances.
- Exhaustion phase – dependent on the time and intensity of the stress.

Resistance responses can help the plant survive stress episodes, but this generally comes at a cost in terms of production or final yield.

Photosynthesis

Wahid *et al.* (2007) considered photosynthesis to be the physiological process that is the most sensitive to heat stress. Ribulose-1,5-bisphosphate carboxylase oxygenase (Rubisco), the first enzyme involved in carbon fixation, is quite tolerant of higher temperatures, and carboxylation will keep increasing, even beyond 50°C. However, as temperatures increase problems occur in C3 plants with increased use of oxygen as a substrate and thus increased photorespiration (Ainsworth and Ort, 2010). Mathur *et al.* (2011) observed that in wheat (*Triticum aestivum*) at 35°C there was no loss of photosynthetic efficiency, however, at 40°C there was a 14% loss of activity and at 45°C there were indications of irreversible damage to the oxygen-evolving complex. Night temperature effects can be significant as well. Shah and Paulsen (2003) found that subjecting wheat plants to a temperature of 35°C day/30°C night after anthesis hastened the normal ontogenetic decline in photosynthetic rates, with effects much more pronounced when associated with drought.

Membranes

Membrane processes are important to functions such as photosynthesis and respiration, but excess heat can damage the fluidity of membranes and disrupt these processes (Barnabas *et al.*, 2008). Wahid *et al.* (2007) reported that high temperature alters the tertiary and quaternary structures of membrane proteins and this can lead to increased membrane permeability and subsequent loss of electrolytes. Membrane thermostability tests can be used as an indicator of heat tolerance in wheat cultivars (Sikder and Paul, 2010).

Proteins, heat shock proteins

Part of the mechanism plants use to cope with environmental stress is the expression of stress proteins, some of which are soluble in water and thus can presumably contribute to stress tolerance via hydration of cellular structures (Wahid *et al.*, 2007). Plant heat stress responses include the production of heat stress transcription factors (HSF) (Zinn *et al.*, 2010). Chauhan *et al.* (2011) subjected wheat plants at different growth stages to temperatures of 37°C and 42°C for 2 hours. Under high temperature many transcriptional factors were up-regulated as well as the expression of heat shock proteins (HSPs) and a large number of unknown proteins. In addition to HSPs, many proteins affecting carbohydrate metabolism, which is strongly correlated to grain weight and yield, are up or down regulated during heat stress (Branlard *et al.*, 2008). Branlard *et al.* (2008) found smaller HSPs of the 20 kDa family expressed 2 to 3 times more at a 34°C/10°C treatment than at 18°C/10°C. For the 70 kDa and 90 dKA families there was a 2.6 and 5 fold increase respectively. The 90 kDa HSPs act as chaperon proteins and also interact with proteins involved in the transcription regulation and signal transduction pathways. HSPs also play a role in plant hardening. Fast acclimatisation to heat is provided by specific HSPs that are encoded within an hour of temperatures exceeding 35°C. They help stabilise membranes and chromatin structures and also play a role in repair. Grigorova *et al.* (2011) observed that HSP expression occurred under both drought and heat stress, but the set of HSPs expressed under each condition could not just be summed to describe the HSPs expressed under the combination of drought and heat stresses. The combined abiotic stress changed plant metabolism in a way not seen in the individual cases. When heat stress has occurred, if there is no further heat stress in subsequent days the number of HSPs declines (Larcher, 2003). Late embryogenesis abundant proteins (LEA) are also known to play a part in heat stress tolerance in wheat by stabilising macro-molecules and enzymes (Farooq *et al.*, 2011).

Osmolytes

Substances referred to as compatible osmolytes accumulate in many plants in response to abiotic stresses such as heat (Wahid *et al.*, 2007). They include a range of low molecular mass organic compounds such as sugars, polyols, proline and glycinebetaine. Osmolytes are known to help decrease cell osmotic potential and help maintain cell turgor pressure and water absorption when the plant is under stress. However, the full functional significance of osmolytes in relation to plant stress is yet to be determined (Krishnan *et al.*, 2011).

Hormones, antioxidants, enzymes

Abscisic acid (ABA) is one of the plant hormones involved in plant response to heat stress. ABA is known to be implicated in osmotic response and mediation of dehydration signaling pathways within cells (Maestri *et al.*, 2002). The hormone auxin is beneficial in the prevention and even reversal of high temperature injury such as male sterility (Oshino *et al.*, 2011; Sakata *et al.*, 2010). However, increasing levels of gibberellin renders plants more sensitive to heat (Maestri *et al.*, 2002).

Heat stress can increase the production of reactive oxygen species (ROS) to damaging levels (Farooq *et al.*, 2011). An important defense mechanism is the production of both enzymic (e.g. ascorbate peroxidase and glutathione) and non-enzymic (e.g. ascorbate and tocopherals) antioxidants (Farooq *et al.*, 2011).

High temperatures can also lead to the irreversible degradation of enzymes through loss of primary covalent bond structure or they become denatured by the loss of tertiary and secondary protein structures. The latter condition is often reversible (Krishnan *et al.*, 2011). The stress response signals of the plant can lead to downstream mechanisms to repair the damaged proteins (Wahid *et al.*, 2007).

Pollen, microsporogenesis

The reproductive development phase of plants is particularly susceptible to damage when exposed to environmental stresses such as excess heat (Abiko *et al.*, 2005). Saini *et al.* (1984) observed that application of 3 days of heat 30°C/30°C to wheat during meiosis, and before anthesis, induced male sterility in pollen mother cells. Examination showed tapetal degeneration leading to pollen grain sterility in approximately 52% of the anthers that had received the heat treatment. Oshino *et al.* (2007) exposed barley plants to temperatures of 30°C/25°C from before and up to meiosis and examined cells in the developing anthers. They reported abnormalities of mitochondria, rough endoplasmic reticulum and nuclear membranes in the pollen mother cells, as well as degradation of the tapetum cells.

Ovaries, megasporogenesis

Saini *et al.* (1983) also investigated the effect of heat stress on pollen tube growth and ovary development in wheat. Once again temperatures of 30°C/30°C were applied at the onset of pollen mother cell meiosis, which corresponds approximately with meiosis in the megaspore mother cells. Six out of 18 ovaries had an abnormal nucleus or embryo sac and 7.4% of pollen tubes in the heat stressed group grew haphazardly and failed to reach the ovary.

Grain number, size

Heat stress immediately prior to and during anthesis can reduce grain set in wheat through a combination of reduced male and female fertility within the spikelet, as previously mentioned, and also as a result of undeveloped or abnormal embryos (Saini *et al.*, 1983). This can result in up to 68% fewer grains at 30°C/30°C compared with control plants (Saini and Aspinall, 1982). Within individual wheat spikelets, heat stress of 35°C for 3 hours causes a small grain set reduction in florets *a* and *b*, but a significant grain set reduction in florets *c* and *d* (Talukder *et al.*, 2010). There is also significant correlation between individual wheat grain mass at maturity and yield (Talukder *et al.*, 2010). Grain filling rate in wheat is also dependent on current assimilates available from photosynthesis and water-soluble carbohydrate storage reserves (Fischer, 2011). The optimum temperature for wheat photosynthesis is around 20 to 30°C, and for assimilate movement out the flag leaf the optimum is also around 30°C (Wahid *et al.*, 2007). Above-average temperatures will also shorten the wheat growth development phases, including the time available to build stem reserves and also the time available for grain filling (Barnabas *et al.*, 2008; Prasad *et al.*, 2008; Rawson, 1986; Tewolde *et al.*, 2006). Thus episodes of heat that are above 30°C and occur in the period before anthesis to the end of grain filling have the potential to reduce significantly wheat grain size and yield at maturity. This is largely due to a combination of decreased grain numbers and reduced resources for grain filling. The degree of asynchrony in flowering has implications for the degree of pollen damage and subsequent reduction in grain number in wheat (Lukac *et al.*, 2011). If a variety has anthesis spread over multiple days, and a one day heat stress event occurs, there is less loss of pollen viability than that which occurs with a short, rapid pollination variety

Grain quality

Episodes of heat greater than 32°C during wheat grain filling can change dough properties by increasing protein levels, although the changed proportion of protein to starch can cause general decreases in dough strength (Appelbee, 2006; Blumenthal *et al.*, 1998). Heat stress of 34 to 35°C or more reduces the synthesis of large molecular weight proteins and increases the production of lower molecular weight gliadin proteins. These proteins are presumed to be acting as heat shock proteins (Blumenthal *et al.*, 1994; Majoul *et al.*, 2004). Heat stress also causes other observable damage to the wheat grain. When a temperature regime of 36°C/31°C was applied to wheat plants for 2 day periods from 3 days prior to anthesis to 10 days after anthesis, grain damage included shrunken grains, notches, opaqueness, shrivelling, splitting and grain sterility (Tashiro and Wardlaw, 1990).

2.3.2 Heat stress effects on wheat growth, development, and yield components

For Australian wheat cropping, with winter crops that are generally sown in autumn, the critical period with respect to heat stress is the period August through to November. This generally covers the plant growth stages from stem elongation through booting (that includes meiosis), inflorescence emergence, anthesis, grain development and grain filling through to maturity. It is this period that is most likely to encounter heat episodes with day temperatures greater than 30°C. This period also includes the reproductive stage that has been suggested as the most susceptible to heat stress damage (Zinn *et al.*, 2010). Table 2-1 summarises some representative wheat heat stress experiments and the effects on yield and yield components of the different treatments. Appendix B (Table A-1) presents a descriptive summary of these and other heat stress experiments.

Common methods in field heat stress experiments include temperature gradient tunnels or transparent heating chambers (Ferris *et al.*, 1998; Talukder *et al.*, 2010; Ugarte *et al.*, 2007; Wheeler *et al.*, 1996) and late sowing (Modarresi *et al.*, 2010; Talukder *et al.*, 2010). Heat stress experiments in glasshouses or polyhouses using pots or tubs are the other methods often used (Prasad *et al.*, 2008; Saini and Aspinall, 1982; Shah and Paulsen, 2003; Wardlaw *et al.*, 1989a; Wardlaw *et al.*, 1989b). In general, daytime temperatures of 30°C or more applied at any stage from booting to anthesis caused a decrease in grain number relative to the controls (Kaur and Behl, 2010; Ugarte *et al.*, 2007; Wardlaw *et al.*, 1989b; Wheeler *et al.*, 1996), while temperatures of 30-35°C immediately post-anthesis and during grain filling caused a decrease in average grain weight (Shah and Paulsen, 2003; Talukder *et al.*, 2010; Wardlaw *et al.*, 1989b). High night-time temperatures (17°C control, 20°C, 24°C treatment) applied from booting to early grain development caused significant drops in grain number (50%) and grain weight (25%) in a pot experiment by Prasad *et al.* (2008). Field experiments show less severe responses to heat stress treatments than pot experiments. This may be due to the higher temperatures that roots are exposed to when grown in pot heat stress experiments (Asseng *et al.*, 2011).

This project concentrates mainly on the effects of heat stress on wheat yield and yield components, but it is noted that many experiments performed both in pots and the field have indicated significant detrimental effects of high temperature on the quality of grain and dough (Appelbee, 2006; Blumenthal *et al.*, 1998; Skylas *et al.*, 2002; Tashiro and Wardlaw, 1990).

Table 2-1. Selected wheat temperature treatment experiments. Cells with yellow highlight are the heat treatment, top line day temp., bottom line night temp. Highlight green indicates the largest effect in that category among the treatments in that experiment.

	Zadoks stage and temperature treatments (top=day, bottom=night)													
Researcher	***30 Stem Elongation***		***40 Booting (meiosis)***		***50 Inflorescence emergence***		***60 Anthesis***		***70 Grain development***		***Grain number***	***Grain weight***	***Grain yield***	***Notes***
(Saini and Aspinall, 1982)	20 20	20 20	20 20	20 20	20 20	20 20	20 20	20 20	20 20	20 20	55%*	44	1251	*%grain set of available fertile florets
	20 20	20 20	30 30	20 20	20 20	20 20	20 20	20 20	20 20	20 20	32%	47**	721	** mg/grain
	20 20	20 20	20 20	30 30	20 20	20 20	20 20	20 20	20 20	20 20	17%	48	433***	***grains/ear
	20 20	20 20	20 20	20 20	30 30	20 20	20 20	20 20	20 20	20 20	28%	48	699	
	20 20	20 20	20 20	20 20	20 20	30 30	20 20	20 20	20 20	20 20	50%	44	1147	
	20 20	20 20	20 20	20 20	20 20	20 20	30 30	20 20	20 20	20 20	55%	42	1210	
	20 20	20 20	20 20	20 20	20 20	20 20	20 20	30 30	20 20	20 20	51%	40	1064	
Researcher	***30 Stem Elongation***		***40 Booting (meiosis)***		***50 Inflorescence emergence***		***60 Anthesis***		***70 Grain development***		***Grain number***	***Grain weight***	***Grain yield***	***Notes***
(Wardlaw *et al.*, 1989b)	18 13	18 13	24 19	24 19	24 19	24 19	18 13	18 13	18 13	18 13	-10%*	-2%	-12%	*% reduction
	18 13	18 13	30 25	30 25	30 25	30 25	18 13	18 13	18 13	18 13	-36%	-4%**	-41%	**%reduction
	18 13	18 13	18 13	18 13	18 13	18 13	18 13	18 13	24 19	24 19	-2%	-15%	- 18%***	****grain weight/ear
	18 13	18 13	18 13	18 13	18 13	18 13	18 13	18 13	30 25	30 25	-8%	-38%	-43%	
Researcher	***30 Stem Elongation***		***40 Booting (meiosis)***		***50 Inflorescence emergence***		***60 Anthesis***		***70 Grain development***		***Grain number***	***Grain weight***	***Grain yield***	***Notes***
(Prasad *et al.*, 2008)	24 14	24 14	24 17	24 17	24 17	24 17	24 17	24 17	24 17	24 17	32*	38	5	*per spike
	24 14	24 14	24 20	24 20	24 20	24 20	24 20	24 20	24 20	24 20	30	34	3.8**	**g/plant
	24 14	24 14	24 23	24 23	24 23	24 23	24 23	24 23	24 23	24 23	15	28	2.5***	***g/plant
Researcher	***30 Stem Elongation***		***40 Booting (meiosis)***		***50 Inflorescence emergence***		***60 Anthesis***		***70 Grain development***		***Grain number***	***Grain weight***	***Grain yield***	***Notes***
(Kaur and Behl, 2010)	26 10	26 10	26 10	26 10	26 10	26 10	26 10	26 10	26 10	26 10	160*	6.6	3.3	* per 5 spikes
	26 10	26 10	33 17	33 17	26 10	26 10	26 10	26 10	26 10	26 10	153	6.0**	3.1	**g per 5 spikes
	26 10	26 10	26 10	26 10	26 10	26 10	26 10	33 17	33 17	26 10	167	6.8	3.2***	***g per plant
	26 10	26 10	33 17	33 17	26 10	26 10	26 10	33 17	33 17	26 10	124	5.0	2.5	
Researcher	***30 Stem Elongation***		***40 Booting (meiosis)***		***50 Inflorescence emergence***		***60 Anthesis***		***70 Grain development***		***Grain number***	***Grain weight***	***Grain yield***	***Notes***
(Talukder *et al.*, 2010)						35					-32%	-10%*	-23%	*approx. IGM
									35		-26%	-11%	-24%**	**Florets c and d

2.4 **Modelling studies**

Loomis *et al.* (1979) distinguished two broad categories of plant models, descriptive and explanatory. Multivariate regression models are descriptive and can be either static or time based. Time based models describe, for example, the developmental rate of a crop as a function of temperature during one or more seasons. Explanatory models are more sophisticated and use dynamic modelling, in an attempt to provide higher level explanation and prediction, by integrating knowledge gained of underlying morphological and physiological processes. However, at the lowest level all such models are ultimately descriptive. Meinke *et al.* (1998) described two common purposes of crop and plant simulation models. A simulation model may be explanatory and used to further our understanding of underlying physiological or other processes. This type of model can be quite detailed and mechanistic. Other model types are predictive and used to predict crop response to a range of environmental scenarios. Meinke *et al.* (1998) argued that the greater the complexity of an explanatory model, the less useful it becomes as a predictive tool. The simulation models reviewed (and used) in this project are almost solely used for the purposes of prediction. Thus, although underlying physiological processes are simulated in predictive models such as APSIM, the simulations need be kept simple enough so as not to make them too difficult to parameterise, and the simulations should not be so detailed that they run the danger of only being useful in a limited range of scenarios.

2.4.1 **Time series models**

One of the challenges of time series models is determining the contribution of a number of covariates to the final result. For example each of rainfall, solar radiation, average temperature, minimum temperatures and maximum temperatures can affect the final yield of a wheat crop. Ideally this type of model produces best results if the following guidelines are used (Lobell, 2010):

- Greater than 20 years of data, however restrict to period when management reasonably constant
- If possible, separate rainfed from irrigated
- For choice of area: bigger is more reliable, but too big is less homogeneous
- Need to detrend any average increase in yield as these may be due to improved management/varieties
- Look for correlations between variables to try to determine the effect of any one of them
- Find areas where climatic variables are not highly correlated if possible.

2.4.2 **Australian historic yield and climatic datasets**

Climatic data at shire level is available from the Australian Government Bureau of Meteorology (BOM). There are one or more BOM weather station records in each of the wheat growing districts for varying periods, in some cases over one hundred years. For example Gunnedah (Station number 55023) has minimum and maximum temperatures and rainfall records extending back to 1877. Solar exposure records extend back to 1990. From the historical records of climate, Lavery *et al,* (1997) used statistical techniques to overcome discontinuities and other inhomgeneities in the historical data of 224 selected weather stations throughout Australia to produce a dataset of 379 high quality rainfall records, covering most of Australia, from which a time-series of Australian wide rainfall could be generated spanning back to 1890, clearly showing the El Nino/Southern Oscillation (ENSO) signal during that period. Jeffrey et al (2001) constructed datasets using spatial interpolation algorithms to fill in data that is often missing from the records.

High quality gridded (approx. 5 km x 5 km) rainfall, temperature and vapour pressure deficit climate datasets have also been developed by the BOM. They were developed using historical Australian weather station data and producing maps showing both climatological and anomaly components (Jones *et al.*, 2009). This supplemented earlier work by Torok and Nicholls (1996) who produced high quality surface-air temperature datasets for Australia covering the period from 1910 to 1993.

Institutions such as the Australian Bureau of Statistics and the Australian Bureau of Agricultural and Resource Economics and Sciences have reasonably complete shire level yield data for Australian wheat crops, covering the last sixty years and more, for most wheat growing areas of Australia. For example, see Hamblin (1993) for analysis of Australian wheat yield trends for the period 1950-1991, or Fitzsimmons (2004) for N.S.W. wheat yield trends 1922-2000, or Stephens and Lyons (1998) for an analysis of selected Australian shire level rainfall-yield relationships. Caution is required interpreting yearly yield averages as they can be either reported in the production year, or the year following, after all crops are in the silo. Hamblin's (1993) yield graphs appear to show shire yield values that are offset one year earlier than those in the table presented by Fitzsimmons (2004).

2.4.3 **Ecophysiological models**

Ecophysiological models attempt to simulate the growth of a crop by understanding and simulating, often in daily time steps, the initial conditions, management and physiological processes that underpin the growth of each component of the crop (White and Hoogenboom, 2010), CropSyst, CSM-CERES and EPIC are commonly used in the US for simulation modelling of wheat growth (White and Hoogenboom, 2010). In Australia, APSIM, which was developed from CERES, is the most commonly used wheat crop simulation program (Fischer, 2011; Peng *et al.*, 2004). Each of these programs simulates plant growth and development by assessing the amount of light intercepted by the canopy, then combining this with the relevant radiation use efficiency (RUE) for the crop type. This provides a factor that can be applied to the growth rate for each phenological stage (White and Hoogenboom, 2010). Many programs use a trapezoid shape to model the plant growth response to temperature. This includes four cardinal points defining a minimum temperature, an optimal range and a maximum temperature. Once the end of the optimal range is reached there may be a steep decline to no growth or senility. There may be different cardinal points depending on the stage of growth (White and Hoogenboom, 2010). The effect of heat stress is in general poorly modelled and in need of further research and model development (Fischer, 2011; White and Hoogenboom, 2010).

2.5 **Conclusion**

Heat stress effects on wheat yields and plant growth generally has been well researched, but there is a need to verify how well this can be predicted by simulation programs, such as APSIM. Possible methods of validation include side by side statistical and simulation modelling, where suitable climatic and yield datasets are available. Other approaches, to separate the effects of heat and drought stress, include container experiments using heat chambers, or irrigated wheat field trials, with control and experimental lines as far as possible having all growth variables similar, apart from the amount of heat stress experienced during anthesis. These methods can not only quantify the effects of heat stress, but also help identify wheat varieties that do have superior heat tolerance.

Little research has been done in the area of analysing historical yields in relation to identified levels of heat stress, or the capabilities of simulation programs such as APSIM to reflect the true effects of short or longer heat episodes. This therefore may be a productive area of research for improving yields for the Australian winter wheat crops, in view of the projected increase in heat events in early to late spring. Simulation plays an important role in identifying the needs and potential direction of new research and modified crop management practices. Research can be directed at ensuring simulation programs accurately reflect the effects of heat spikes, perhaps of just one day, or episodes covering many days. Simulations may need to take more account of reproductive damage and the stages where it is most susceptible. Other factors, such as hardening due to a more gradual temperature rise may need to be factored in. Other possible areas include the cooling effects of evapotranspiration, or including humidity and wind factors to get more accurate simulations results. However, the quest for detailed accuracy may not always produce the best general simulation package. The aim is to improve without being too specific and at the same time retain APSIM's general usefulness by not making the parameterisation too complex.

Chapter 3 – Statistical model building, validation and comparison with the APSIM simulation predictions.

3.1 Introduction

3.1.1 Model types

For predicting the yield performance of a crop such as wheat under current or future climate scenarios, two main types of models can be used. Ecophysiological models attempt to capture the main underlying biological processes of plant growth and seed production and then use this knowledge to predict future performance. Statistical or time series models, on the other hand, analyse the relationships between historical records of variables such as weather, soil factors and yield and use this knowledge to build predictive models of future crop performance (Lobell, 2010). However, Lobell and Burke (2010) note that all statistical models rely to some extent on knowledge of physical process and all ecophysiological models rely to some extent on statistical records.

Both model types can have limitations. One drawback of time series modelling is that crop records and climate datasets can only provide a limited view of the real extent of the effects of heat stress episodes on wheat yield and quality. Yield datasets tend to be averaged over multiple districts that encompass a range of soil types and other environmental variables, such as solar radiation, cloud cover and rainfall. Management regimes and cultivar types vary from field to field and farm to farm. Climate datasets are not always complete. Other yield related environmental variables, such as rainfall and average temperature, and the problem of co-linearity between yield related variables, makes it difficult to separate the effects heat stress effects alone, although one possibility is to search for areas where there appears to be less co-linearity between variables (Lobell, 2010). On the other hand, ecophysiological models are based on the scientific theory of how the underlying crop growth mechanisms operate. When simulating historical yields, variables such as management practice, cultivar types, or soil types have to be generalised.

Time series modelling can help elucidate the relationship between historical wheat yields and weather variables. This approach can be useful when there is a sufficiently long period of yield and weather variable datasets; Lobell (2010) suggests a data training period of at least 20 years. However, the choice of weather variables to use is a choice that is not always obvious. The choice can depend on both availability and suitability of variables. Although some weather datasets at first glance appear to have long records for a number of variables, closer inspection shows there is not a complete or reliable record of all weather variables. For example, in the Queensland Government Specialised Information for Land Owners (SILO) climate database, the variables such as solar radiation, pan evaporation and vapour pressure often had suspiciously similar values, often spanning weeks, in many of the years prior to 1970. Another consideration is the months during which each variable is relevant, whether it should considered for the whole growing season, or select only those months that cover certain developmental stages of the wheat crop. This in turn depends on which area of the Australian wheat cropping zone is being considered: in the more southern latitudes of the wheat cropping area, such as Victoria, developmental stages can be a month or more later than in the northern areas such as Queensland. Co-linearity of variables is perhaps one of the most difficult aspects of time series modelling. As explained later in this chapter, there is a strong inverse correlation between growing season rainfall and growing season temperature in Australia. Attempts to separate the effects of these and other temperature related variables are not always successful and requires some initial processing, such as calculating monthly or seasonal high degree hours (HDH) and then using the calculated variables as input to a regression analysis.

3.1.2 **Time series studies of wheat yields and higher temperatures**

For wheat, no studies using time series data have been identified in the literature that examine the effects of heat stress *per se* on Australian wheat crops. However, diurnal temperature range (DTR) has been studied. Nicholls (1997) used high-quality Australian rainfall and temperature datasets, covering the period 1952-1992, to estimate the effects of climate change on Australian wheat. His main finding was that a decrease in DTR has partly contributed to an increase in wheat yields, possibly due to the increase in average minimum temperature and consequently fewer frosts. In other studies, Lobell (2007) used Food and Agriculture Organization (FAO) of the United Nations yield statistics (1961-2002) for wheat along with gridded climate datasets and found a negative correlation between DTR and wheat yield in both Canada and Australia. There was a positive relationship in France that the author speculated may be due to increased solar radiation associated with the increased DTR. For crops other than wheat, Schlenker and Roberts (2009) estimated the relationship between temperature and yields for corn, soybeans and cotton in the US. They found that nonlinear temperature effects indicated severe damage to crops when temperatures of 30°C and above are encountered. Lobell (2010) examined US maize yields 1950-2005 along with an hourly weather dataset. Part of the investigation was the effect of Growing Degree Days (GDD) > 30°C, calculated on an hourly time step. There was a significant negative correlation between GDD > 30°C and yield. However GDD > 30°C was also correlated to average temperature, which also correlated to yield. As the authors pointed out, this is one of the difficulties of time series modelling, identifying the effects of individual variables on the result. One of the serious shortcomings of statistical models is that of co-linearity between predictor variables and often low signal to noise ratios in weather or yield records at some locations (Lobell and Burke, 2010). On the positive side, statistical models do not have to rely on calibration data; their accuracy is more transparent as correlation coefficients and confidence intervals can be included in the results. The usefulness of statistical models also improves with higher spatial scales (Lobell and Burke, 2010).

3.1.3 **APSIM**

APSIM is a well validated cropping simulation program, developed in Australia. It was chosen as the ecophysiological program for comparison with the time series model using the same independent validation set. APSIM has been extensively tested in a range of environments (Asseng *et al.*, 2011; Keating *et al.*, 2003; Wang *et al.*, 2009). Observed wheat yields for a period of over 6 years near Wagga Wagga, NSW showed a reasonable match to model predictions (Wang *et al.*, 2009). Carberry *et al.* (2009) also evaluated APSIM's performance by simulating 17 years of commercial wheat crops from around the Australian wheat belt and comparing these with the actual data of farm experiments. The performance of the APSIM simulations was quite credible when compared to the yield data obtained from the field experiments.

3.1.4 **Previous APSIM studies on the effects of heat stress on Australian wheat**

Many of the previous simulation studies using APSIM centre on predictions of future wheat crop performance using different climate change scenarios. In many cases historic climate records have been used as the basis of the simulations and these are then modified to reflect a range of projected temperature rises. Some of these studies focussed on increased CO_2 levels in combination with increased temperatures, for example Reyenga *et al.* (1999), Wang *et al.* (2009), and Luo *et al.* (2005).

Few studies have focused on temperature alone. Power *et al.* (2004) studied the effects of long term increase in minimum winter temperature in conjunction with ENSO and its effects on wheat yields at Gunnedah, in NSW. A trend in increased minimum temperatures was associated with increased wheat yield when the effects of other climatic factors were removed. Asseng *et al.* (2011) used APSIM to quantify the effects of temperature variability on past wheat yields in Australia. Using the simulation they were able to separate the effects of temperature from other factors. Their results indicated that variations of average growing system temperature of as little as 2°C could cause yield reductions of up to 50%. They attributed most of this decline to increased leaf senescence at temperatures > 34°C. Wang *et al.* (2009) used 117 years (1889-2006) of SILO weather station records at Wagga Wagga to simulate yields using a baseline temperature and then yields with 1°C to 4°C of simulated warming. The simulated yields dropped by an average of approximately 8% for each degree of warming.

3.1.5 **Research aims**

In this study the wheat yield records from six shires (Carrathool, Coolamon, Narrandera, Temora, Lockhart and Wagga Wagga) in south eastern NSW (that together make up much of the wheat cropping area within Statistical Division 150 (SD150)) are analysed, using time series modelling and the APSIM simulations, to address the following research questions:

- What is the relationship between yield, higher temperatures and growing season rainfall? Can the effects be separated?
- Can time series modelling reveal to what extent do episodes of above average maximum temperatures limit Australian rainfed wheat yields?

- Are the APSIM predictions similar to the time series model predictions when using the same time period, area and weather records?

3.2 **Methods**

3.2.1 **Overview**

Figure 3-1 is a flowchart that shows an overview of the dual modelling approach and the points of comparison of the model predictions. This approach builds a time series model using historical wheat yields and weather station records, validates the model against a later period of yields and weather records, and then runs the APSIM simulations for the same areas, using the same weather records.

3.2.2 **Why use both times series and APSIM?**

A reason for using both time series and simulation modelling was as a cross check of the higher temperature scenario predictions of the time series model against the APSIM predictions using the same weather data. It is also useful to compare the predictions of the two approaches against the observed yield data to see which method gave the best predictions, both for individual shires and for the same combined shires in SD150 (Figure 3-2, Figure 3-3).

By comparing the APSIM predictions with observed yields, an indication of how well the APSIM simulated episodes of high temperature might be apparent. By comparing the difference between the APSIM predicted and observed yields, versus high temperature hours for each season, there should be some indication of whether APSIM is over or under predicting yields in high temperature seasons.

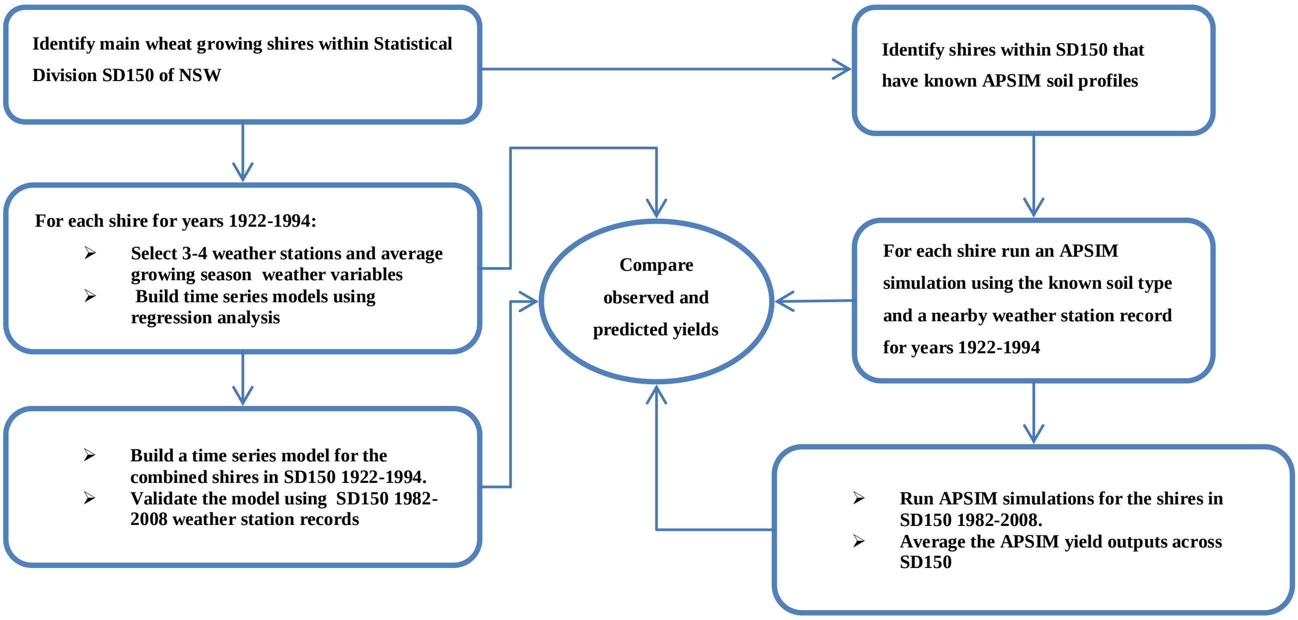


Figure 3-1. Flow chart of the approach used to identify and compare predicted versus observed temperature and rainfall effects on wheat cropping in the Statistical Division 150 (SD150) of NSW for temperature and rainfall effects for the years 1922-2008.

3.2.3 Area selection

Important considerations were which areas and what spatial extent to include in the study. Too large an area can risk including different climatic zones together, such as areas with more dominant winter or summer rainfall, and within these zones there may be lighter sandy soils, that drain relatively quickly and thus rain may be beneficial, or there may be heavier clay soils where too much rainfall during the growing season leads to water logging. For this reason, and because of the need for the cropped areas in each of the shires over the study period to be reasonably consistent, a relatively small area in the south eastern portion of the NSW wheat cropping zone was chosen for this study. Area selection is further described in the methods section.

The approach used in this study was to fit and train the time series model using shire wheat yield records from the period 1922-1994 and then validate this model using Statistical Division records (the Statistical Division being a larger area that encompasses the shires) for the period 1982-2008. In parallel, APSIM simulations were run for each of the shires and also for the Statistical Division to enable a comparison between the model results (see flowchart in Figure 3-1).

The cropping areas (Fitzsimmons, 2004) were analysed for the six most consistent shires that were also part of a single Statistical Division, where the initial cropping area in 1922 did not increase or decrease markedly over the study period up to 1994. The reason for selecting shires with the most consistent cropping areas was that this should help eliminate yield variation over the period due to expansion of cropping into more marginal areas, that may occur in years with higher wheat prices, leading to relatively lower yields in those areas. The shires selected were: Carrathool, Coolamon, Narrandera, Wagga Wagga, Lockhart and Temora that also largely comprise Statistical Division 150 (SD150) (Figure 3-2 and Figure 3-3).

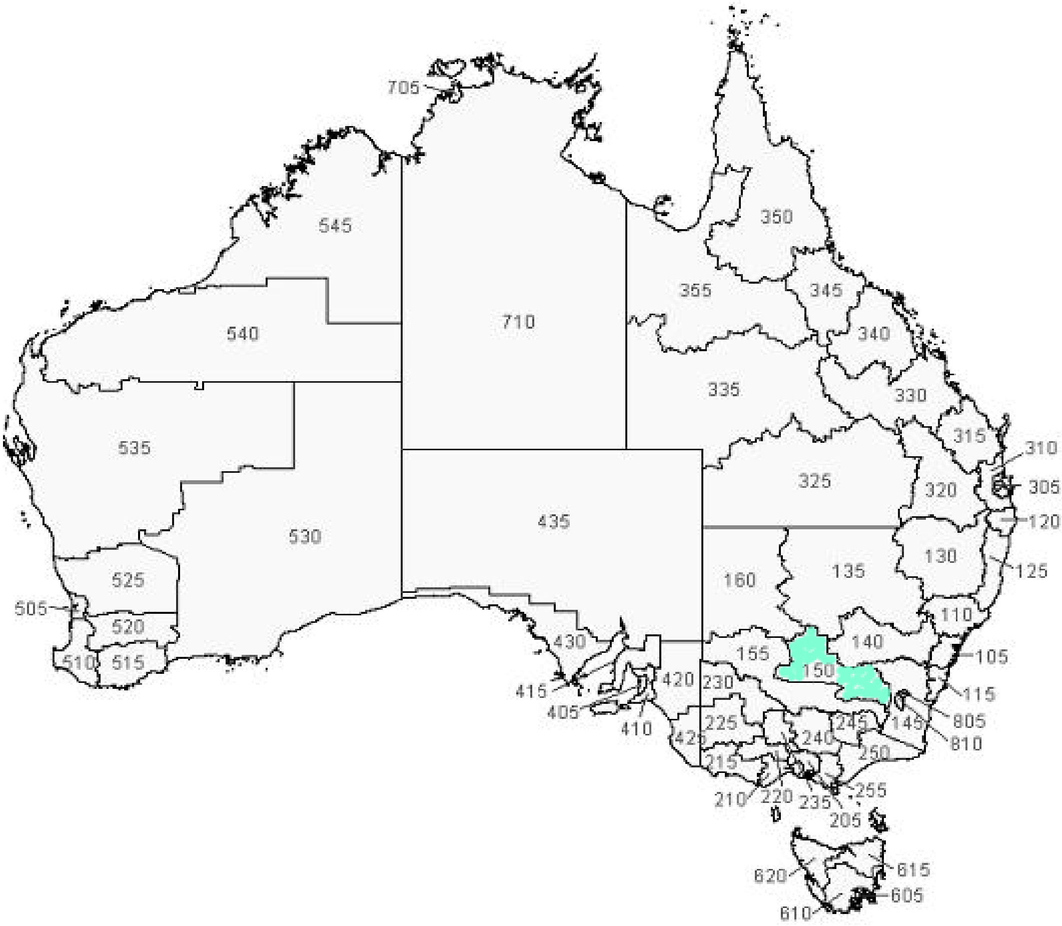


Figure 3-2. Australian Statistical Divisions 2004 map (ABS, 2005). Statistical Division 150 (SD150) (lower right corner of map) is highlighted.

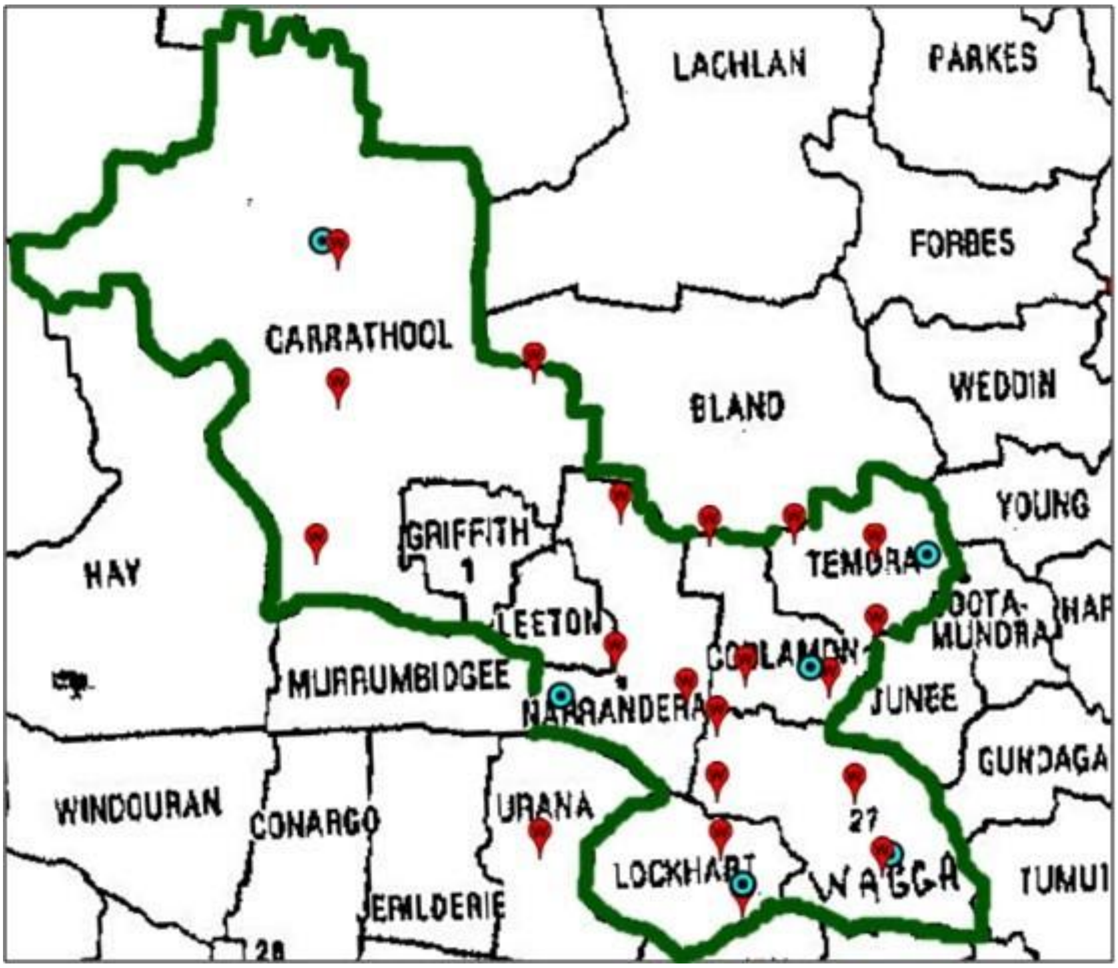


Figure 3-3. Selected NSW shires within Statistical Division (SD150). The locations of Patched Point Data (PPD) weather stations are marked with the red balloons containing a 'w' symbol and the APSIM characterised soil locations are marked with blue circles containing a dot. The selected shires are Carrathool, Coolamon, Narrandera, Wagga Wagga, Lockhart and Temora.

3.2.4 Yield datasets

Available yield datasets included those used in Hamblin and Kyneur's (1993) shire level analysis of the relationships between wheat yield and soil fertility were obtained from the Australian Bureau of Agricultural and Resource Economics (ABARE). The datasets cover most shires in the wheat cropping areas of Australia and contain annual yields from the year 1949 through to 1990. The yield year shown in the datasets is in reality the year after the crop was grown, as this is apparently when the statistics become available, after the crop is in the silo. Therefore in any comparison with weather and other environment variables the yield year has to be adjusted to the preceding year.

Statistical Divisions represent large regional geographic regions covering relatively homogeneous economic and social areas in Australia. Datasets covering wheat yields for Australian Statistical Divisions from 1982 to 2008 were obtained from ABARE, courtesy of James Walcott, Senior Scientist, Mitigation and Adaptation Sciences. These datasets also state the yield year as the year after the actual year the crop was grown. The other dataset was wheat yield figures covering New South Wales (NSW) shires for the years 1922-1994 and were available from the book prepared by Fitzsimmons (2004). In this case, by comparing with the NSW yield figures from Hamblin and Kyneur (1993), it was concluded that Fitzsimmons' yield dates represent the actual year the crop was grown.

Table 3-1. Wheat yield datasets that were available and considered for this project.

Source	Yield data	Area data
Hamblin and Kyneur (1993)	Australian shires 1949-1990	no
ABARE	Australian Statistical Divisions 1982-2008	yes
Fitzsimmons (2004)	NSW shires 1922-1994	yes

The Hamblin and Kyneur (1993) dataset has yields for all Australian shires (Table 3-1) but was not used as: a) the time span was less than the Fitzsimmons (2004) dataset and b) there was no data available on the actual areas cropped each year in each shire. Area data was considered important as a wide variation in area cropped over the study period can introduce yet another variable that influences average yield data per shire. The yield dataset from Fitzsimmons (2004) has a continuous record for NSW shires from 1922 to 1994. This dataset was chosen because a) it spanned a relatively long period and b) allowed yield to weather variable comparisons between similar agro-ecological zones (groups of shires) and c) it contained cropping areas for each shire for each year of production, thus allowing selection of shires with most consistent cropping areas. The other dataset used was for Australian Statistical Divisions with yields and areas for the years 1982-2008 that covers all the wheat cropping areas in Australia but at a later time frame than the Fitzsimmons (2004) dataset.

A complicating factor in selecting yield datasets is the shire boundary changes and amalgamations that began in approximately 1996 in many parts of Australia. Hence, shire data later than 1996 cannot be compared reliably with earlier shire data as the shire size may have grown or the shire in many cases ceased to exist.

3.2.5 **Observed yield de-trending**

When comparing observed yields across an area, such as a shire, with simulation results, robust de-trending and comparison methods are required. The former should remove yield advances due to technology. The latter needs to express year to year yield changes in a format such as percentage deviation from a mean, rather than as absolute values.

One objective of the study was a comparison of the effects of temperature on yields between different shires. Another objective was to compare observed and modelled yields from both regression analysis and APSIM (see flowchart Figure 3-1). To facilitate these comparisons weather variables and yields values were converted to relative figures, i.e. percentage deviations from the mean, rather than using absolute values. Regression lines (Appendix C Figure A-2) were then fitted to the set of yield values for each shire. The yield trends for the period 1922-1994 in general were not linear. A 2^{nd} order polynomial was a reasonable compromise for creating the trend lines. For each season, the proportional yield deviation was then calculated as:

Yield Delta% (YD) = (yield – trend)/trend) * 100.

Since the earlier data (1922-1994) consisted of shire yields and the later data (1982-2008) were Statistical Division yields, an approximation to SD150 yields was made using the average of the six shires. The result could be verified by comparing the overlapping years (1982-1994) of the two periods. On average, the shire yields were 0.2 t/ha higher than the SD150 yields. This may be because SD150 includes some extra smaller more marginal shires that were not included in the earlier period shires analysis due to their variability in cropping area. To compensate for this the SD150 yields were incremented by 0.2 for the years 1982-2008, making the de-trended yield curve consistent across the two periods.

For Statistical Division 150 (SD150), as in much of Australia, the years 1982-2008 were marked by recurrent drought. To de-trend the yields for these years a method similar to that of Lake (2012) was used. This method first ignores drought years, by replacing drought year values with an average of yields from adjacent non-drought years, and then calculates a five year moving average yield. To obtain the five year average for the initial years for SD150 an average yield was calculated by averaging the six shire yields (component shires of SD150) for the four years immediately prior to 1982. Drought years were then interpreted as years where growing season rainfall was 20% or more below average. The drought year yields were replaced by the average value of the nearest four non-drought years. The five year moving average was then calculated as the average of the current year's yield and the four preceding years yields. The resultant moving average showed yields plateaued around the year 2000 and then decreased with the hint of an upward trend in the final two years up to 2008 (Figure 3-5). This result was similar to that obtained by Lake (2012) for Australian wheat yields, except Lake's data did not show the final minor upward trend seen in the SD150 results. Lake suggested that the cause of the general downward trend was an increase in cropping intensity combined with a concurrent reduction in the use of legume leys.

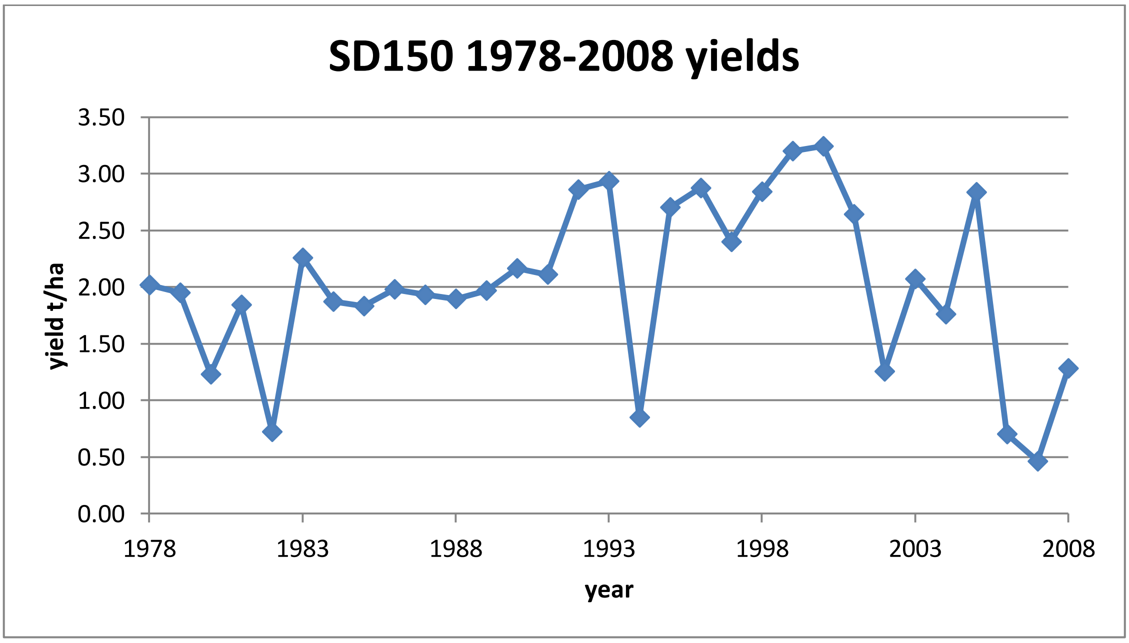


Figure 3-4. SD150 wheat yields in t/ha for the years 1978-2008.

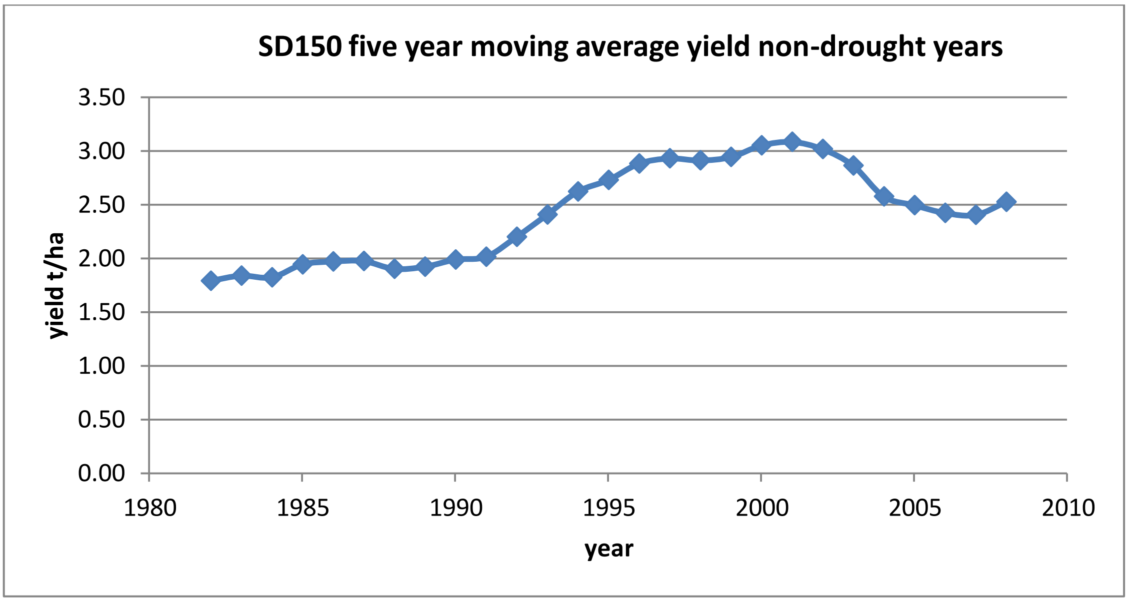


Figure 3-5. Five year moving average of SD150 yields in t/ha for years 1982-2008 obtained by replacing drought year yields with the average of the closest non-drought year yields.

3.2.6 Weather data

Historical Australian climate data for NSW was obtained from the Queensland Government Specialised Information for Land Owners (SILO) climate database (http://www.longpaddock.qld.gov.au/silo). Details on the accuracy of this dataset were described by Jeffrey *et al.* (2001). The dataset contains continuous daily weather records in multiple formats including one formatted for input to APSIM. The dataset contains daily climate variables from as early as 1889 up to the current year (2012). One choice of format of this data is the Patched Point Dataset (PPD) that is available for an extensive (approx. 4600) subset of Australian meteorological stations. The data for these stations have had missing data patched using linear spline interpolation of data from surrounding stations. The variables available include daily rainfall, solar radiation, maximum and minimum temperatures, pan evaporation and vapour pressure. These data are useful for Shire level analysis of wheat yields as, in most cases, multiple PPD stations are available in each Shire. This enables an estimate of average weather variable values across the cropping areas of these shires.

3.2.7 **Weather station selection**

In each shire, representative PPD stations that were evenly spaced across the shire were selected (see Figure 3-3 – red balloons marked 'W', and also Table 3-8). Selection of weather stations in some shires took into account the location of predominantly cropping areas within the shires, avoiding mountainous and forested areas. Satellite imagery (Google Earth) was used as a guide. In some cases (for example Lockhart shire), where only two weather stations could be found within the shire, a third weather station was selected from an adjoining shire as close as possible to the boundary of the shire under study. It was considered that, since only yield responses to temperature and rainfall fluctuations were being investigated, using a weather station from an adjacent shire should not greatly affect the results.

3.2.8 **High Temperature Degree Hours (HDH)**

An explanation of how to derive the area of temperature stress above a critical temperature based on a daily sine wave, with only daily minimum (Tmin) and daily maximum (Tmax) given, is described in Bristow and Abrecht (1991). This is based on the previous work of Parton and Logan (1981) who devised a model for diurnal variation in air temperature. The method uses a sine wave function to describe the rise and fall of the daily temperature and an exponential function to describe the decay in temperature during the night until early morning (Figure 3-6).

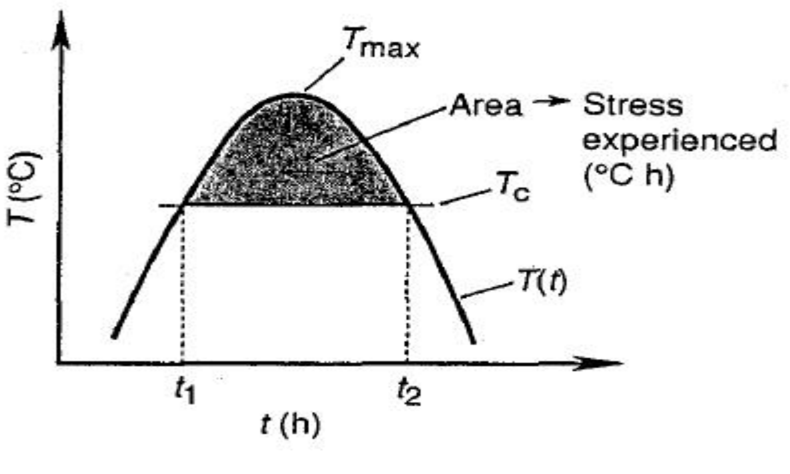


Figure 3-6. High temperature stress area of daily diurnal temperature range represented as a sine wave. Tc is the critical temperature above which stress is experienced. Diagram copied from Bristow and Abrecht (1991).

The following formulae, based on the Bristow and Abrecht (1991) method, were used to calculate HDH:

$$t1 = (D/pi)*asin((Tc-Tmin)/(Tmax-Tmin))$$

$$t2 = D - t1$$

$$HDH = (Tmin-Tc)*(t2-t1) - (Tmax-Tmin)*(D/pi)*(cos(pi*t2/D) - cos(pi*t1/D))$$

where D = day length hours, Tc = critical temperature and Tmin and Tmax are the minimum and maximum temperature for the current day.

The Bristow and Abrecht (1991) method was chosen as the most suitable to calculate the HDH values for this study based on the analysis of different methods for estimating daily high temperature degree hours by Roltsch *et al.*(1999).

3.2.9 **HDH thresholds**

Farooq *et al.* (2011) reviewed the published literature on the level of temperature elevation that can reduce wheat yields during the reproductive period. The maximum temperatures for each reproductive stage are shown in Table 3-2. The table indicates an optimum temperature corresponding to each reproductive stage. Temperatures above these optimums can significantly reduce grain yield. However, most of the experimental setups from which these figures were derived did not involve rainfed field wheat. Experimental setups included container plants (Al-Khatib and Paulsen, 1984; Gibson and Paulsen, 1999; Stone and Nicolas, 1995; Wollenweber *et al.*, 2003; Yang *et al.*, 2002), simulation studies (Anwar *et al.*, 2007; Asseng *et al.*, 2011), heat gradient tunnels with controlled water supply (Ferris *et al.*, 1998) and irrigated field wheat (Amani *et al.*, 1996). Wheat crops in Australia are predominantly rainfed. SILO weather station records from 1922-2008 also show an inverse relationship between maximum temperature and rainfall in south eastern NSW (Appendix C Figure A-5). The combination of heat and water stress are known to be more damaging than either stress individually (Barnabas *et al.*, 2008) and much of the effect is on photosynthetic processes (Shah and Paulsen, 2003). Thus the threshold values from Table 3-2 cannot be assumed to be an absolute guide as to how wheat will react to temperatures in a rainfed, field grown situation. With this in mind a range of threshold temperatures was experimented with, but keeping the same approximate inter-stage relativity as the threshold temperatures from Table 3-2.

Table 3-2. Threshold temperatures for reproductive growth stages of wheat indicating where plant growth and grain development damage can begin to occur. From Farooq *et al.* (2011).

Stage	Mean temperature (°C)
Terminal spikelet	21.4 ± 2.33
Anthesis	32.0 ± 1.74
Grain filling	34.3 ± 2.66

The sowing date in each season is affected by a range of factors such as rainfall, soil moisture, and management. The rate of growth is also affected by factors such as temperature and wheat variety type. Therefore, a range of dates has to be assumed for the occurrence of each phenological stage.

Table 3-3. Approximate sowing times and reproductive stage timing for wheat crops in south eastern NSW.

Date	Stage
Late April to early June	Sowing
Late July to early September	Terminal Spikelet
Late August to early October	Anthesis
October - November	Grain Filling

The threshold temperatures in Table 3-2 indicate the level at which damage occurs to the wheat plant, with associated yield reduction. However, even temperatures lower than this may affect yield by shortening the time for each stage to complete, thus possibly resulting in less accumulation of resources and subsequently less grain production (Anwar *et al.*, 2007). To model potentially negative effects on yield during periods of elevated temperatures, an overlapping scheme was used (Table 3-4), with the threshold temperature for each reproductive stage chosen at a level similar to the values for the corresponding stages in Table 3-2. Techniques were also tried with threshold temperatures set at -1˚C and -2˚C below and at +1˚C and +2˚C above those in Table 3-4, and also a technique where threshold temperature was stepped up each month rather than ramped, but in general the regression analysis coefficients had fewer P values less than 0.05 and the regressions had lower R values than those produced using the method shown in Table 3-4.

Table 3-4. South eastern NSW: dates and high temperature thresholds in °C for calculating High Degree Hours (HDH). Stages: ts = terminal spikelet, at = anthesis, gf = grain filling, ve = vegetative.

Month	**Jul**				**Aug**				**Sep**				**Oct**				**Nov**			
Stages	ve	ve	ts	ts	ts	ts	ts	ts	ts	ts										
							at	at	at	at	at	at	at	at						
											gf	gf	gf	gf	gf	gf	gf	gf	gf	gf
HDH threshold					20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35

3.2.10 **Calculated weather variables**

Of the weather variables available from the SILO dataset, only the daily temperature and rainfall values were used. Although solar radiation, pan evaporation and vapour pressure values were also available, initial inspection of data from early years cast some doubt on their integrity, especially when readings had the same or similar values for multiple days or even weeks in some cases. In later years (e.g. 1970 onwards) these figures appear more reliable.

Daily temperature and rainfall values were evaluated for the growing season only, defined as the months of April to November inclusive. For each shire the daily weather station values were averaged and then processed into the new calculated variables outlined in Table 3-5 below. Thus for the selected weather stations (Table 3-8), in each shire, for each day of the growing season, the mean maximum and minimum temperature was calculated. From these daily averages the growing season average maximum and minimum temperature were calculated. From these same figures the growing season diurnal temperature range (DTR) and average temperature could also be calculated for each shire. Total and monthly values for HDH were calculated for the months of August, September, October and November as described previously. The number of days where the temperature in each shire exceeded 30°C in each shire was also recorded along with the number of days with temperatures less than 2°C in each of August and September for each season. A combined shires values was also calculated for each of the variables, representing the six shires that are part of SD150. The weather variables were all calculated for the time period from 1922-2008.

3.2.11 Selection of calculated weather variable selection for regression analysis

The calculated weather variables were then evaluated both by correlation to yield, and cross correlation, before choosing likely candidates to be used in the regression analysis of yield against rainfall and temperature for all the shires in the study.

Table 3-5. Weather station calculated weather variables. All, except the first four, were evaluated as inputs to multiple regression analysis as predictors of wheat yields in south eastern NSW. The first four variables were then used in analysis of the residuals of model predicted yields versus observed.

Variable Name	Description
HDH20Aug	High Degree Hours Aug.: (sum of max. temp. hours over 20°C in Aug.)
HDH25Sep	High Degree Hours Sept: (sum of max. temp. hours over 25°C in Sep.)
HDH30Oct	High Degree Hours Oct.: (sum of max. temp. hours over 30°C in Oct.)
HDH35Nov	High Degree Hours Nov.: (sum of max. temp. hours over 35°C in Nov.)
HDH	High Degree Hours total Aug. – Nov.
minTSeason	Average min. temp. for growing season
maxTSeason	Average max. temp. for growing season
DTRSeason	Average diurnal temp. range for growing season
avTSeason	Average temp. for growing season
lt2Aug	Number of days temperature less than 2°C in Aug.
lt2Sep	Number of days temperature less than 2°C in Sep.
rfSeason	Growing season rainfall (mm)
gt30	Number of days during growing season max. temp. > 30°C

Initial examination of correlation of calculated variables to seasonal percentage yield variations indicated that the strongest negative correlations were diurnal temperature range (DTR), high degree hours (HDH) and average maximum growing season temperature, respectively (Table 3-6). The strongest positive correlations were growing season rainfall and average minimum growing season temperature, respectively.

Table 3-6. Correlation of calculated weather variables to yield delta% for combined shires comprising SD150 for years1922-1994.

HDH20Aug	HDH25Sep	HDH30Oct	HDH35Nov	HDH	minTSeaso	maxTSeaso	DTRSeason	avTSeason	lt2Aug	lt2Sep	rfSeason	gt30
-0.39	-0.37	-0.47	-0.35	-0.66	0.36	-0.59	-0.72	-0.29	-0.33	-0.33	0.67	-0.44

As well as correlation analysis, graphs of calculated weather variables against yield delta percentages (Figure 3-7) were used to aid in the selection of variables for times series regression analysis. Although DTRSeason shows a strong negative correlation to yield (-0.72) and rfSeason has a strong positive correlation to yield (0.67), there is also a strong negative cross correlation between rfSeason and DTRSeason (-0.89, Table 3-7). Thus DTR was not included in the regression analysis.

Table 3-7. Correlation matrix between selected variables for combined shires (SD150) for years 1922-1994. Note that DTR has the highest negative correlation to yield delta%, but it also has the strongest negative correlation to growing season rainfall. HDH also has a high negative correlation to yield delta%, but less of a negative correlation to growing season rainfall. Most of the high temperature related variables all have a high correlation (R>0.5) to growing season rainfall, the exception is days greater than 30°C (gt30).

	HDH	minTSeasor	maxTSeaso	DTRSeason	avTSeason	lt2Aug	lt2Sep	rfSeason	gt30
minTSeason	-0.08								
maxTSeason	0.64	0.07							
DTRSeason	0.61	-0.49	0.83						
avTSeason	0.49	0.58	0.85	0.42					
lt2Aug	0.20	-0.45	0.01	0.26	-0.22				
lt2Sep	0.08	-0.63	-0.11	0.26	-0.42	0.28			
rfSeason	-0.63	0.38	-0.77	-0.89	-0.43	-0.25	-0.19		
gt30	0.59	0.04	0.51	0.42	0.43	0.22	-0.04	-0.43	
yld delta%	-0.66	0.36	-0.59	-0.72	-0.29	-0.33	-0.33	0.67	-0.44

For rainfall, the growing season (April to November inclusive) rainfall for each shire for each year over the study period was used. When growing season rainfall is plotted against yield for the SD150 shires (Figure 3-7, e), there was a reasonable linearity from the low rainfall values up to approximately 30% above average growing season rainfall values, and then there was no clear relationship as rainfall increased beyond that point.

Therefore, for the regression analysis, values above 30% average rainfall were excluded as periods of above average HDH are almost non-existent in the high rainfall years (Figure

3-8) and it was conjectured that yields tended to drop off in these years due to other factors such as water logging, disease, inability to harvest the crop and so forth.

3.2.12 **Regression analysis**

Two datasets were used, as mentioned earlier, the 1922-1994 shire level yield data set and the 1982-2008 Statistical Division yield dataset. Six of the shires in the earlier dataset make up a large portion of the wheat cropping area of SD150. Therefore it was decided to use the earlier shire level dataset to fit the time series model, using regression analysis, and then use the later SD150 data as an independent data set to validate the model.

The regression analysis method was to identify the most likely candidate variables selected on the basis of both their correlation to yield variation and taking into account the amount of cross correlation between variables. DTR was excluded because of its close inverse relationship to seasonal rainfall. The most likely candidates were growing season rainfall and either one, or a combination of, gt30, maxTSeason, HDH and HDH30Oct. After excluding years where rfSeason was greater than 30% above average, as explained earlier, a linear relationship was consider appropriate. The variable relationship that produced the most significant coefficients was:

Yield Delta% = RF% + HDH

where RF% is the growing season rainfall deviation from average as a percentage and HDH is the high degree hours. For regression results and statistics for individual shires and for SD150 see APPENDIX C Time Series and APSIM modelling.

3.2.13 **Time series model validation**

Once the combined shires regression model was built by averaging the weather variables and yields from all selected weather stations across the six shires for 1922-1994, the yields could then be predicted for the later 1982-2008 period, using the later SD150 yields and weather station values. The period 1990-2008 contained periods of drought and high temperature exceeding much of what was experienced in most of the earlier period, so this approach was considered to be a good test of the accuracy and precision of the time series model.

3.2.14 **APSIM soil profile selection**

The APSIM toolbox presents a selection of soil profiles for selected sites in Australia and other countries. Many of these soils have already been parameterised for wheat modelling. Soil profiles were available from the toolbox for all shires in the study. Some shires had two or more profiles available. These are shown in Figure 3-3, as blue circles with black dots. Soil profile names and nearby weather station names are shown in Table 3-8 below. Only one soil profile from each shire was used, those used a marked with an ‘*’.

Table 3-8. NSW shires with related SILO weather stations and the APSIM soil profiles. `*` marks the entries used for the APSIM simulations.

Shire	Weather stations	APSIM soil type id.
Carrathool	CarrathoolM075014	
	*HillstonAP075032	*Hillston No696
	Merriwagga075142	
	RankinSprings075057	
Temora	Ariah074002	
	Sebastopol073114	
	*Temora073038	*Temora No823
Coolamon	Ardlethan-74000	APSIM-543
	Ganmain-74044	
	*Marrar-74068	*Coolamon No175
Narrandera	Barellan-74005	
	GrongGrong-74008	
	*Narrandera-074082	*Narrandera No700
Wagga	Currawarna-074022	
	*Tarcutta-72008	*Tarcutta No178
	TheRock-074021	APSIM-549-YP
	Wagga-72150	
Lockhart	*Henty-74053	*Henty No701
	MittagongHS-74074	APSIM-755
	Urana-74110	

3.2.15 **APSIM (V7.5) simulations**

For each of Carrathool, Temora, Coolamon, Narrandera, Wagga Wagga and Lockhart shires an APSIM soil profile was chosen along with a nearby SILO weather station (Table 3-8). A single weather station was used, rather than averaging a selection of stations from each shire. Inspection of the daily readings from weather stations within each shire showed only minor variations between them, so the results should not have been affected to any significant degree.

Using the APSIM template ‘Continuous Wheat Simulation’ the following management options were then chosen:

Sowing rule:

start 15-Apr

end 10-Jun

must sow? yes

Cultivar: hartog

Climate Control:

- Change in maximum temperature (°C): 0
- Change in minimum temperature (°C): 0
- Relative change in daily rainfall (%): 0
- Fertiliser at sowing: 150 (kg/ha) urea_N
- Harvesting rule: harvest when ripe
- Surface organic matter
- Organic matter type: wheat
- Initial surface residue (kg/ha): 1000
- C:N ratio of initial residue: 80
- Fraction of residue standing: 0

- All other options were left at the default settings for the chosen soil (using APSIM version 7.5).

3.2.16 Statistical analysis

To compare single site APSIM simulation wheat yield predictions with shire level observed yields, each yearly yield value was expressed as a percentage of the mean yield over the analysis period (1922-1994) and the validation period (1982-2008), respectively. Similarly, growing season rainfalls were expressed as percentage deviations from the mean over each period. High degree hours were expressed as absolute values, as one purpose of the study was to get an indication of the relationship between HDH values and yield reductions.

To evaluate the accuracy and precision of the model predictions, and the APSIM simulations, against the observed yields, the coefficient of determination, root mean square error, slope and intercept of the linear regression line were calculated. Graphical analyses of residuals were also used to evaluate the quality of the time series models and the APSIM simulations.

3.3 **Results**

3.3.1 **Relationship between yield and climate variables**

Relationship between yields and calculated climate variables

Calculated climate variables compared graphically to percentage yield deviations for each shire (1922-1994) indicated a linear relationship for HDH and gt30 and a curvilinear relationship for maxTseason, DTR. rfSeason is only compared up to 30% above the season average illustrating the linear relationship to yield up to the rainfall value. Above 30% the relationship was no longer linear and yields begin to drop as rainfall exceeds 50% of average. This is shown graphically in the APPENDIX C Time Series and APSIM modelling, Figure A-4. Growing season rainfall (R^2 =0.60) has the strongest positive relationship to yield while DTR (R^2 =0.60) and HDH (R^2 =0.43) have the strongest negative correlations. However, DTR also has a strong negative correlation with rainfall (R^2 =0.89, Table 3-7).

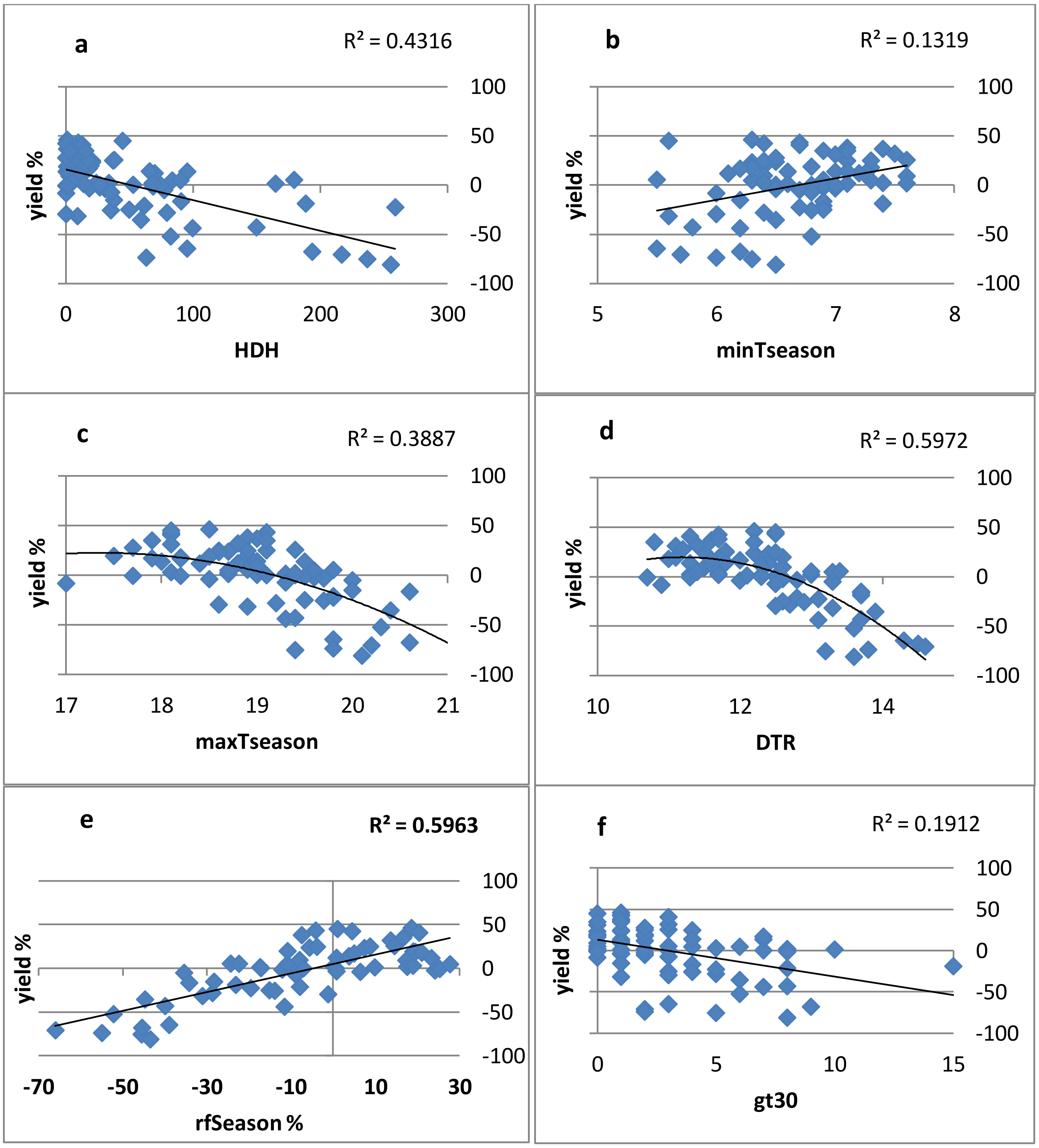
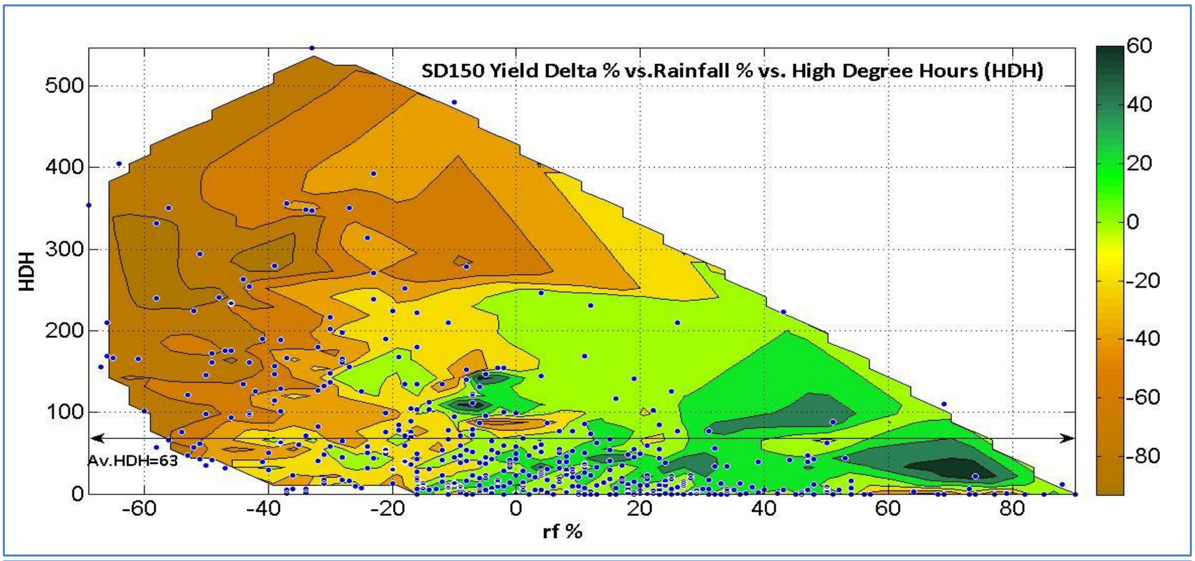


Figure 3-7. SD150 yield % variations plotted against calculated weather variables for years 1922-1994. Vertical axes are yield delta%. Plots are: a) High Degree Hours b) Minimum average growing season temperature c) Maximum average growing season temperature d) average growing season diurnal temperature range e) growing season rainfall f) growing season days with temperature greater than 30°C.

Relationship between yields, HDH and growing season rainfall

The three way relationship between HDH, growing season rainfall % and yield % is illustrated by the 3D contour plot in Figure 3-8 (top). There is a close inverse relationship between growing season rainfall and HDH, however, higher values of HDH are most damaging when growing season rainfall is in the 15 -45% below average range. Also when HDH is above 250, regardless of rainfall, yields drop to 40% or more below average. The lower diagram shows the growing season rainfall in mm. It indicates that anytime rainfall drops below 200 mm yield is severely reduced. Above average yields are only achieved in the 200-300 mm rainfall band if HDH remains below 250 at 300 mm rainfall ramping down to a HDH of approximately 100 at 200 mm rainfall.



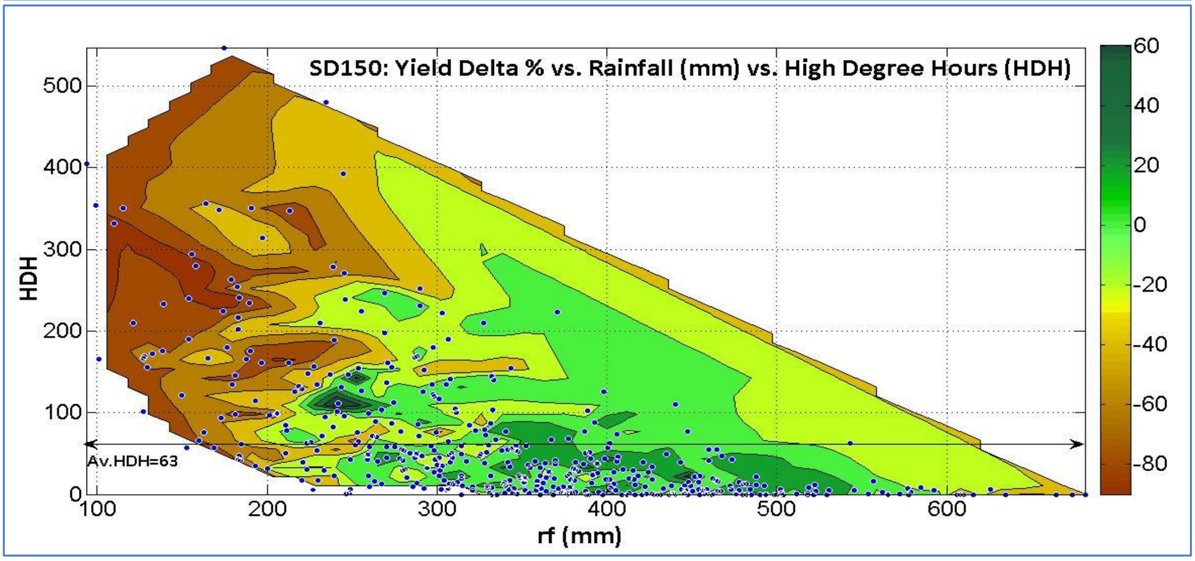


Figure 3-8. Statistical Division 150 (SD150) 3D contour plot showing relationship between yield delta%, HDH and growing season rainfall% (top), yield delta%, HDH and growing season rainfall in mm (bottom). Colour bar is yield% deviation from trend. Horizontal double headed arrow is average HDH for SD150. Blue dots are individual season results from each shire in SD150 for years 1922-1994.

3.3.2 **Shire times series regression models 1922-1994**

For the six selected shires the growing season rainfall decreases and the seasonal HDH increases moving from the south eastern most shire (Wagga Wagga) to the north western most shire (Carrathool). This is illustrated in Figure 3-9 below.

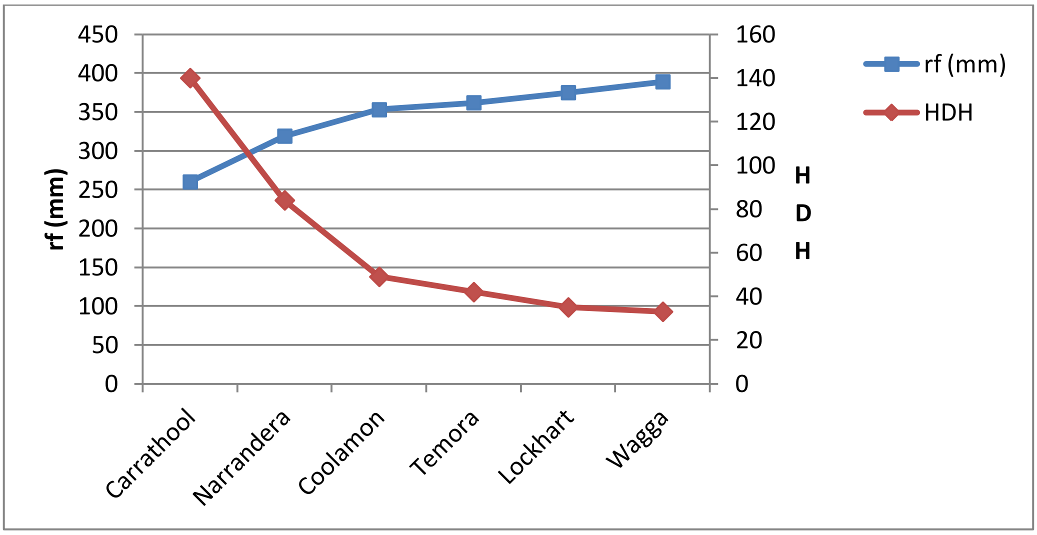


Figure 3-9. The blue line is growing season rainfall, which trends upwards as the geographical locations of the shires move north west to south east, while average HDH (red line) decreases from north west to south east.

A summary of coefficients of the individual regression models, built for each of the six shires for the period 1922-1994, are listed in order in Table 3-9 below , from the warmest and driest (north west most) shire to the coolest and wettest shire (Wagga Wagga).

A method of interpreting the results, for example in Carrathool shire is: if growing season rainfall is average (rf% = 0) and there were no high degree hours (HDH = 0), then the yield would be 15.1% above the long term detrended average. However, for each additional 10 HDH there will be a 0.9% drop in the yield relative to the long term average, and for each 10% drop in rainfall there will a 10.4% drop in yield relative to the long term average.

Growing season rainfall percent (in the range up to 30% above average) has a beneficial effect on yields, more so in the north western shires of Carrathool and Narrandera However, if absolute rather than relative rainfall amounts are considered, the rainfall effect is even more marked. Carrathool has an average rainfall of 260 mm while Wagga Wagga's average is 390 mm. The rfSeason regression model coefficients for Carrathool and Wagga Wagga are 1.04 and 0.57, respectively. Thus a 26 mm (10%) rainfall variation leads to a 10.4% variation in yield in Carrathool, while a 39 mm (10%) rainfall variation in Wagga Wagga only results in a 5.7% yield variation.

HDH increments always have a negative effect. The effect is less in the two north western shires of Carrathool and Narrandera than in the more south eastern shires. Carrathool and Narrandera have a higher average HDH (140, 84) than the other four shires (Coolamon 49, Temora 42, Lockhart 35, Wagga Wagga 33). Thus, increments in HDH from high base HDH values seem to have less negative effect on yield than increments from low base values. This is possibly because of HDH exceeding the threshold value of 250, at which point the rate of incremental yield loss may be less because the crop is already badly damaged and close to crop failure (Figure 3-8).

Table 3-9. Individual time series models for six shires in south eastern NSW fitted by regression analysis using yield and weather station data from years 1922-1994. '*' indicates significance P<0.05 and '' P<0.01.**

Shire	Intercept	rfSeason	HDH
Carrathool	15.10*	1.04**	-0.09*
Narrandera	12.22**	0.93**	-0.09*
Coolamon	10.52**	0.88**	-0.16**
Temora	12.46**	0.73**	-0.13
Lockhart	14.13**	0.57**	-0.18**
Wagga	9.85**	0.57**	-0.16*

3.3.3 **Shire APSIM simulations 1922-1994**

For each shire an APSIM (v7.5) simulation was run covering the period 1922-1994 as outlined in the methods section. To get some indication of how well APSIM handles periods of high temperatures and/or low rainfall, the residuals (difference between the predicted and observed yields) from the APSIM simulations for the years 1922-1994 were plotted against both growing season rainfall and HDH (Figure 3-10).

For growing season rainfall, there is an indication that APSIM over-predicts the yield at high rainfall (>50% above average) in Carrathool. In the shire of Wagga Wagga (the coolest and wettest shire) there appears a pattern of over-prediction of yields at low rainfall and under-prediction when rainfall is above average. When HDH is high in Wagga Wagga, APSIM also shows a pattern of over-predictions of yields, most pronounced when HDH is > 150. Thus, for Wagga Wagga, APSIM tends to over-predict yields during seasons of low rainfall and also seasons with high HDH. However, growing season rainfall and HDH do have a strong negative correlation as noted in Table 3-7, so a further analysis was to plot the APSIM residuals for 1922-1994 against the derived variables for HDH during each growth stage, HDH20Aug, HDH25Sep, HDH30Oct and HDH35Nov (Figure 3-11). This was done for Wagga Wagga only, as it showed the greatest effects of HDH on the APSIM predictions. By breaking HDH effects down into monthly, or developmental stage heat effects on predictions (Figure 3-11), the three occasions when HDH30Oct (i.e. high degree hours exceeding 30°C in October) exceeded 60 in Wagga Wagga can be identified. On these occasions APSIM over-predicted the yield by between 20 and 50%.

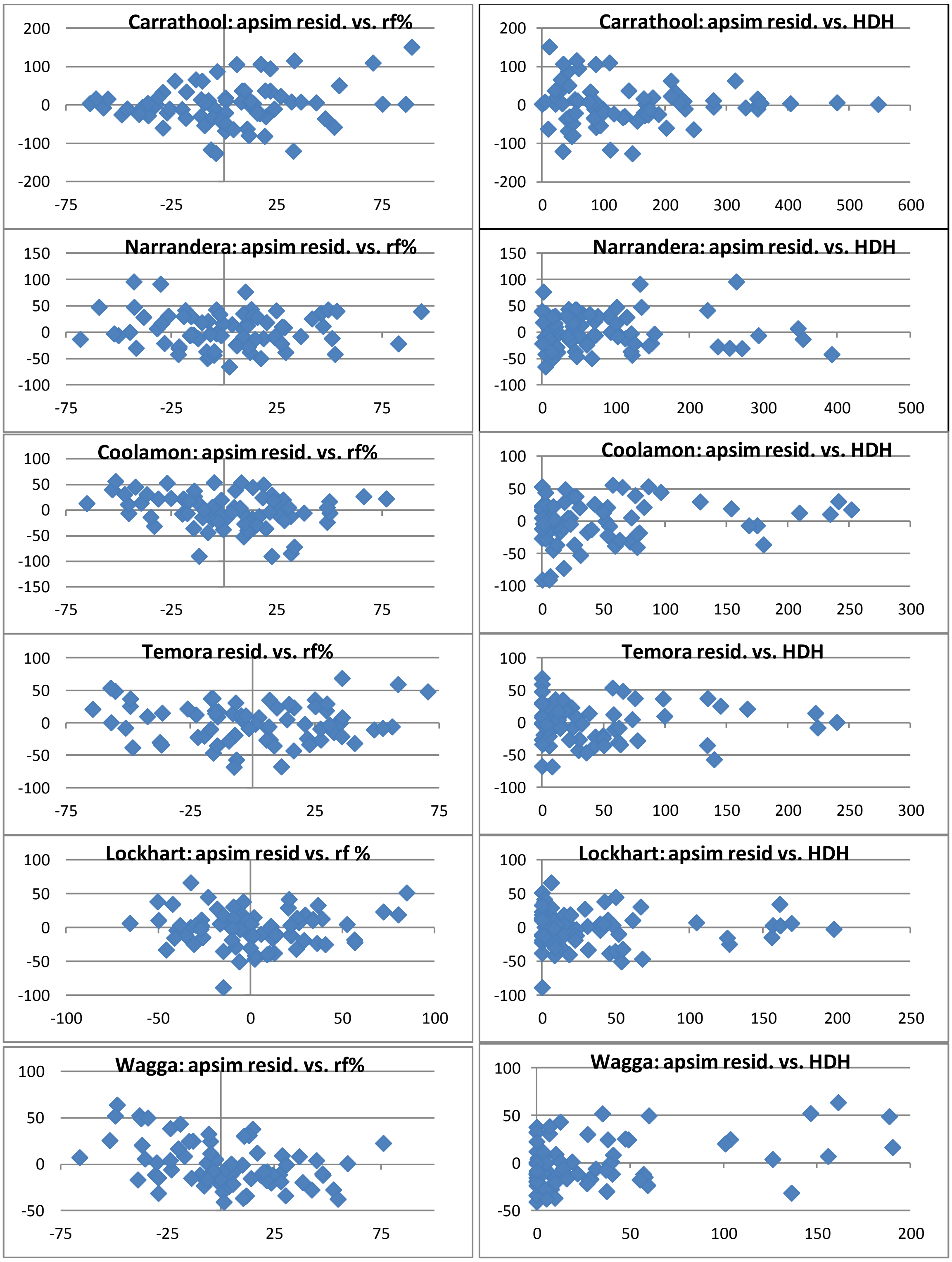


Figure 3-10. Residuals from the APSIM prediction (yield deviation from mean %) minus observed (yield deviation from mean %), for years 1922-1994, plotted against growing season rainfall (left column) and high degree hours (HDH) (right column) for each of the selected shires in south eastern NSW. The order of the shires is from hottest and driest (top) to coolest and wettest (bottom). Vertical axis in each plot is residual.

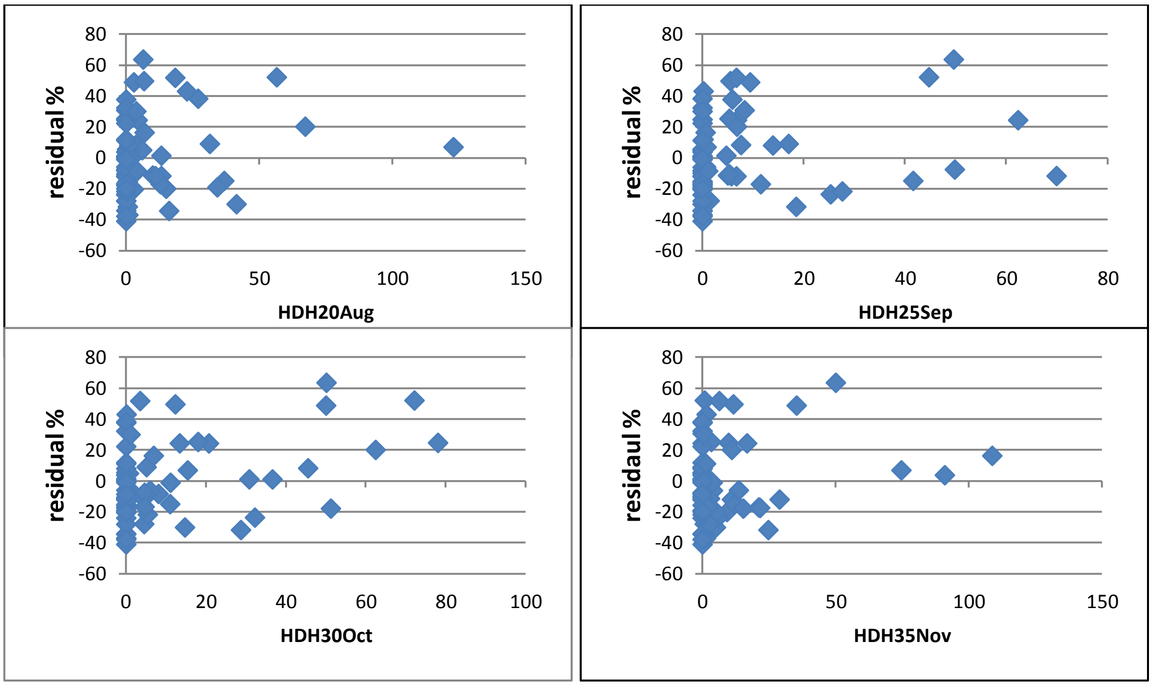


Figure 3-11. Wagga Wagga: residuals from the APSIM prediction (yield deviation from mean %) minus observed (yield deviation from mean %), for years 1922-1994, plotted against high degree hours (HDH) >20°C August (HDH20Aug), HDH > 25°C September (HDH25Sep), HDH > 30°C October (HDH30Oct) and HDH > 35°C November (HDH35Nov). The greatest deviation can be seen for the APSIM predictions in October, where yields have been generally over-predicted when HDH30Oct is > 50.

3.3.4 **Combined shire (SD150) time series model 1922-1994**

The result of the regression analysis for the time series model using averaged yield and weather station record data across all six shires, for the years 1922-1994, is summarised in Table 3-10. As expected the coefficient values for growing season rainfall and HDH are intermediate to the range of values for the individual shires (Table 3-9).

Table 3-10. Time series models for SD150 built by regression analysis using yield and weather station data from years 1922-1994. '*' indicates significance P<0.05 and '' P<0.01.**

Area	Intercept	rfSeason	HDH
SD150	10.51**	0.84**	-0.13**

3.3.5 **Time series model validation using independent 1982-2008 data set**

Using the time series model, built with the 1922-1994 combined shire data, predictions were made for the period 1982-2008 using weather stations records averaged across SD150. Although the model was built by using data from years 1922-1994, but excluding wet years (growing season rainfall > 30% above average), the validation included all years 1982-2008, as this enables a better comparison with the data of the APSIM simulations for SD150 for the years 1982-2008.

The validation results are illustrated in three ways:

Figure 3-12 shows the time series comparison of modelled and observed yield. Figure 3-13 shows the residuals against growing season rainfall and HDH. Figure 3-13 is a plot of observed against predicted yield and includes linear regression, RMSE and coefficient of determination statistics. The last mentioned (Figure 3-16) is discussed further in the APSIM/time series model comparison section.

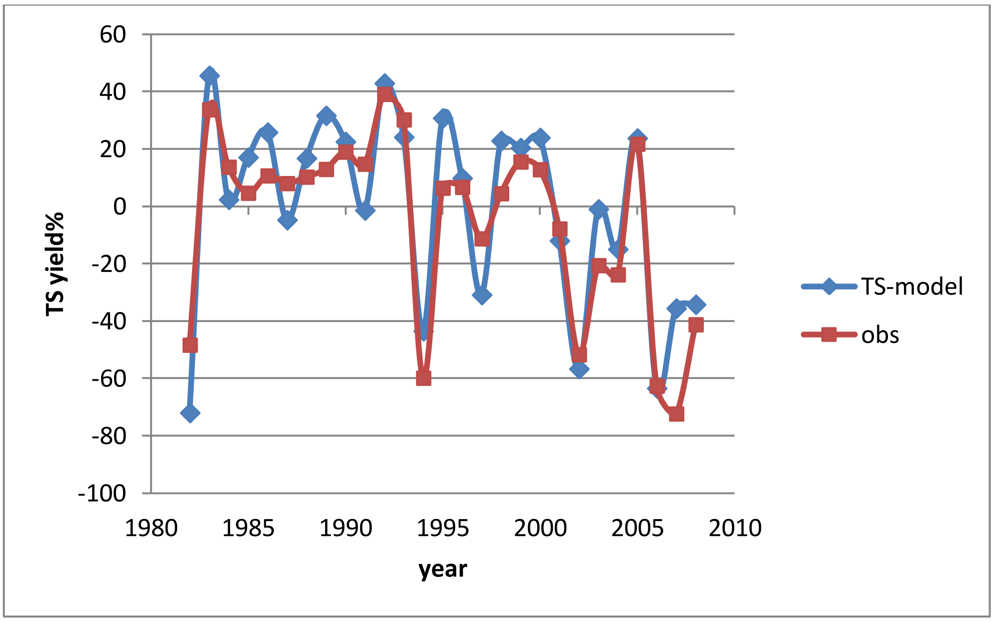


Figure 3-12.Time series model predictions of yield delta% for SD150 for the years 1982-2008 (blue line) and observed yield delta % (red line).

Examination of residuals (from predicted vs. observed yields) in (Figure 3-13a) indicates a tendency for the time series model to over-predict yields in the period 2004-2008. There is also a tendency to over-predict yields as the growing season rainfall increases, especially when the rainfall is above average (Figure 3-13b). When the HDH is greater than approximately 150, there is also a tendency for the model to predict lower yields than those observed (Figure 3-13c).

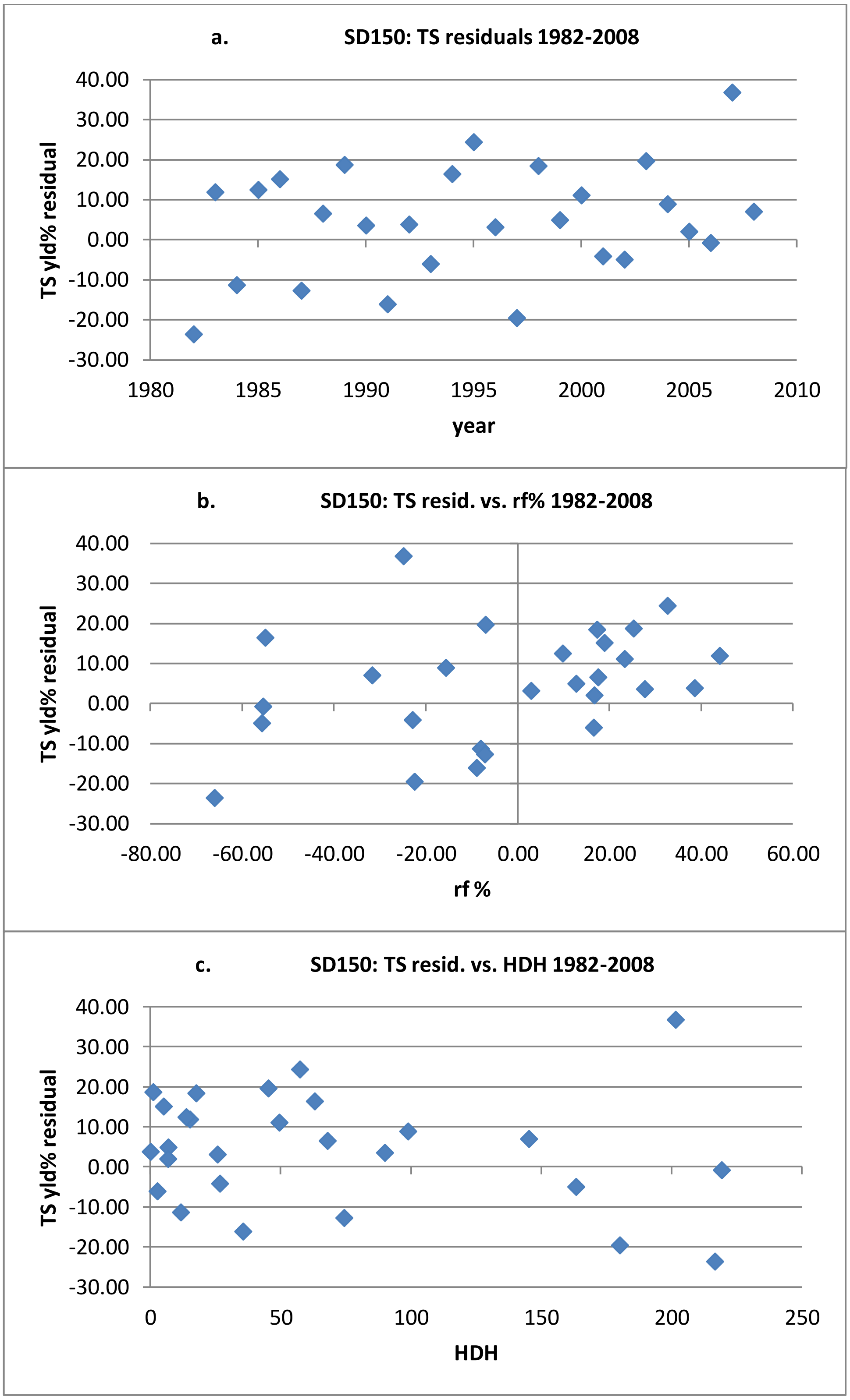


Figure 3-13. Time series model plot of (a) years (b) growing season rainfall % (c) HDH against residuals from observed versus predicted yields for SD150, 1982-2008. The model is showing a tendency to over-predict yields at higher rainfalls. It also over-predicts yields from 2003 onwards, possibly a problem with the yield trend removal process.

3.3.6 **APSIM simulations using 1982-2008 data**

The results of the APSIM (v7.5) simulation, using the averaged yield from six major wheat cropping shires contained within SD150, for the years 1982-2008, are presented in Figure 3-14 and Figure 3-15, and also in the model comparison section (Figure 3-16). Figure 3-14 gives an overview of the APSIM predicted yield, expressed as a percentage deviation from the APSIM predicted average yield (1982-2008), compared with observed yields. The observed yields are the percentage deviation from the five year moving average for 1982-2008 (explained previously in the methods section).

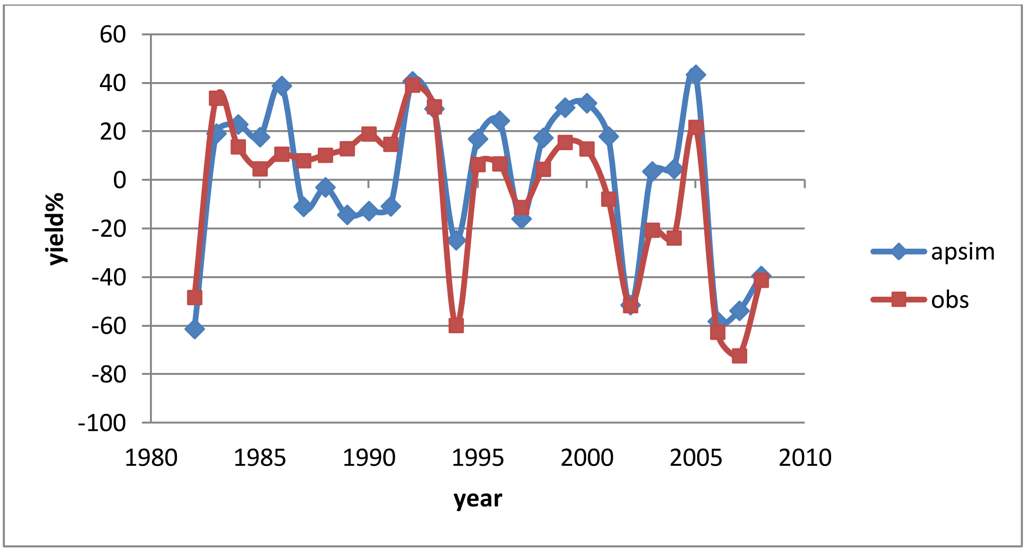


Figure 3-14. the APSIM simulation predictions of yield delta% for SD150 for the years 1982-1994 (blue line) and observed yield delta % (red line).

The residuals plotted against year in Figure 3-15a indicate a tendency for the APSIM model to over-predict yields in the period 2000-2008. However, residuals plotted against both growing season rainfall percentage (Figure 3-15b) and HDH (Figure 3-15c) indicate no significant trends.

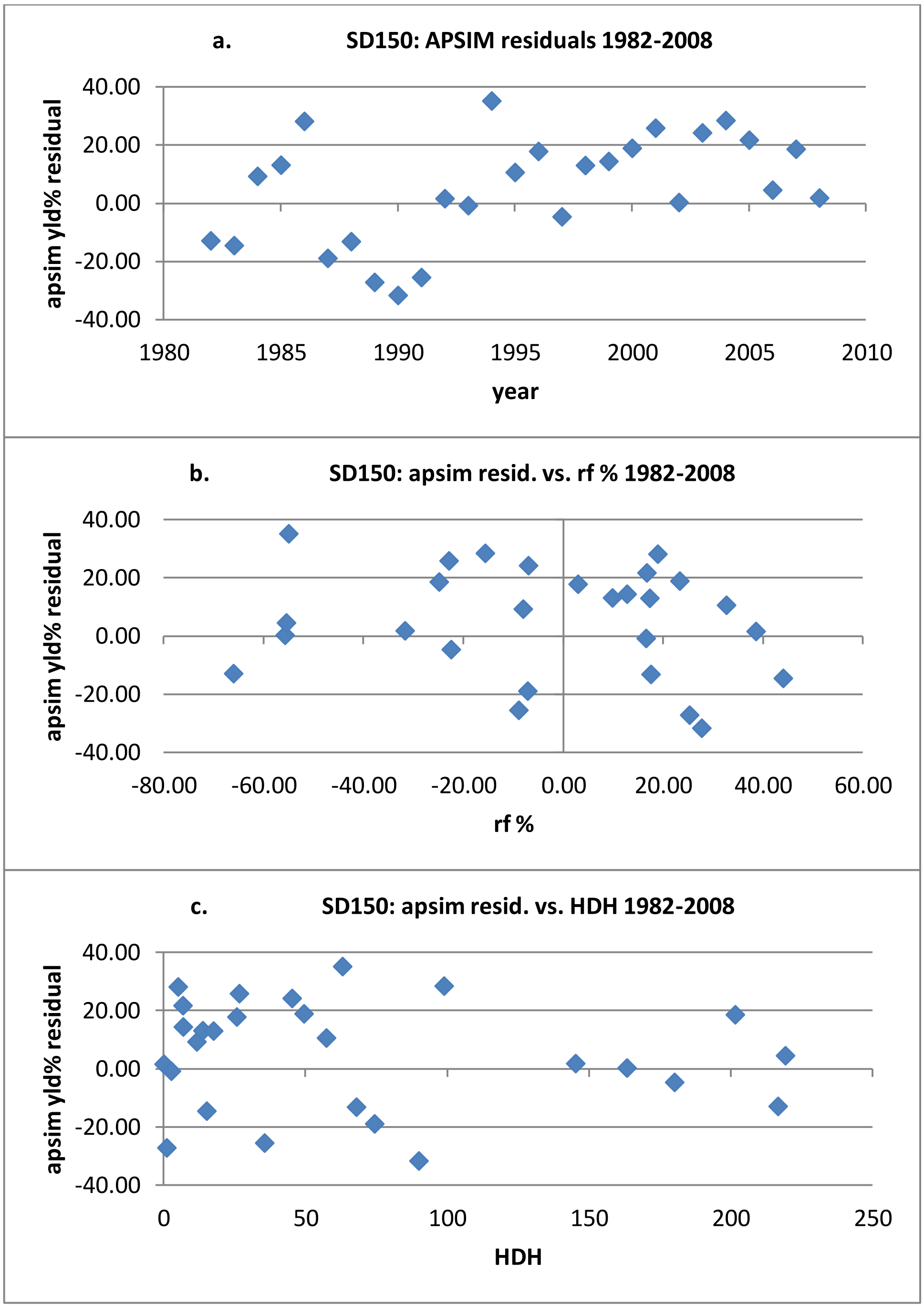


Figure 3-15. the APSIM simulations: plot of (a) years (b) growing season rainfall % (c) HDH, against residuals from observed versus predicted yields for SD150, 1982-2008. From 1998 onwards the APSIM model over-predicted yields. This may indicate a problem with the yield trend removal process, possibly due to the number of drought years in this period obscuring the real trend.

3.3.7 Comparison of time series and the APSIM models

The predicted yields and observed yields for both the time series and the APSIM models are compared in Figure 3-16, (a) and (b). When the performance of each model is evaluated by slope, coefficient of determination and RMSE, the time series model is superior to APSIM. Offsets are similar, i.e. both models predict yields approximately 4% above the observed (possibly related to the yield de-trending method). The slope of the time series model is closer to a 1:1 relationship than the APSIM model (0.95 for time series and 0.84 for APSIM).

Despite the preceding superior statistical measures for the time series model, at low yields (<40% below average yields), the APSIM predictions appear more precise (grouped closer together). However, for yields >0% above average, the time series model predictions were more precise.

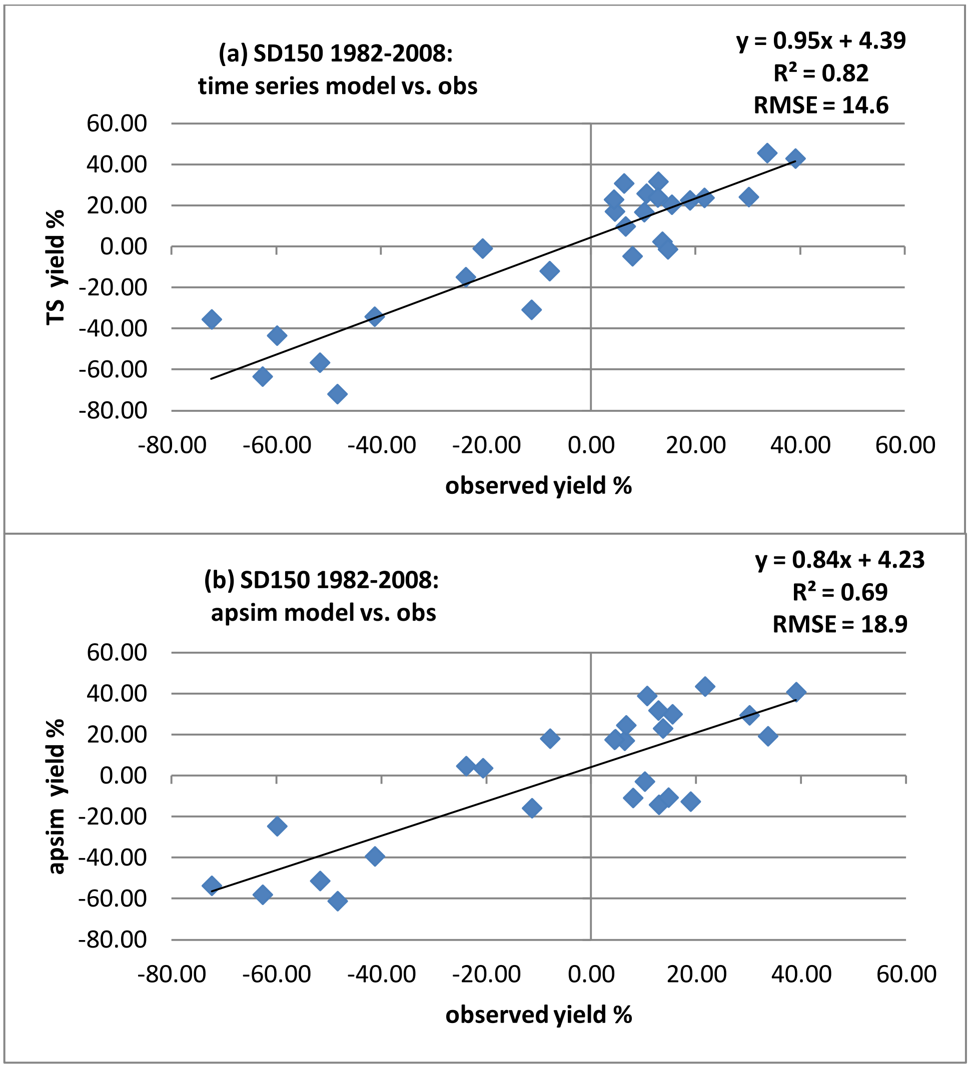


Figure 3-16. SD150 1982-2008: Comparison of observed and predicted yields for (a) time series model (top) and (b) APSIM.

3.4 **Discussion**

Although this study found growing season rainfall and HDH to be the best predictors of wheat yields in southern NSW, others (Stephens and Lyons, 1998; Stephens *et al.*, 1994) found that rainfall alone, combined with a weighted monthly index, was a useful predictor. Monthly rainfall distribution was also considered in this study, but high temperature had higher correlation to yield than any single month's rainfall figures. Nicholls (1997) attributed 30-50% of Australian wheat yield increases from 1952-1992 to temperature variations, in particular a rising trend in minimum temperatures, and concluded that fluctuations in diurnal temperature range (DTR) were the major determinants of annual yields. In the current study however, rainfall was the dominant determinant of yield. The difference may in part be because Nicholls included all Australian wheat growing areas in his calculations and rainfall distribution varies in its effects across the wheat growing areas of Australia. In Western Australia, excessive winter rainfall can have a negative effect due to water-logging, while in the eastern states some winter rainfall is generally positive (Stephens and Lyons, 1998).

Disentangling rainfall and temperature effects in rainfed field crops using statistical models can be challenging, due to problems of co-linearity (Lobell and Burke, 2010). This study found that rainfall is beneficial up to a point, and then yields flattened and dropped as rainfall exceeds 30% of growing season average. HDH however, always has a negative effect. Roberts *et al.* (2012) and Schlenker and Roberts (2009) obtained similar results using qualitative data in their studies of non-linear effects of heat on corn and other crops (soybean and cotton) in the U.S.A. Further evidence of the separate relationship of HDH and rainfall to yield was revealed by 3D plots where HDH has its most noticeable effect within a rainfall band of 15-45% below average rainfall. The effects of HDH become more severe as growing season rainfall drops from approximately 300 mm to 200 mm. Lobell *et al.* (2011) obtained a similar result in their analyses on climatic impacts on African maize crops, each degree day over 30°C decreased yields by 1% under optimal rainfall but the yield reduction increased to 1.7% under drought conditions. With moderate warming scenarios, Lobell *et al.* (2013) suggested that the yield reductions associated with the accumulation of temperatures above 30°C may not be solely due to reproductive organ damage, but because increased vapour pressure deficit causes slower growth and consequently reduced yields. However, the 3D plots indicated that higher temperatures that lead to a growing season HDH of 250 or more are associated with a 40% or more reduction in yield, no matter what the rainfall. It is probable that yield reduction at this level of heat exposure is caused by reproductive organ damage (Saini and Aspinall, 1982), or increased leaf senescence (Asseng *et al.*, 2011). If growing season rainfall drops below an absolute value of 200 mm then yield also suffers severely. The yield, HDH, rainfall relationship varies across the study area (SD150), from north west to south east. Individual shire multiple regression analyses reveal the higher importance of rainfall in the north west, where a dry season is more likely to be approaching the critical 200 mm level, than in the wetter south eastern shires.

For SD150 (using the average of the six shires) the time series model indicates an 8.4% reduction in yield for each 10% reduction in rainfall and a 1.3% reduction in yield for each extra 10 HDH. To compare my data with other research, for each year, weather records were reprocessed to reveal how much HDH increased when there was a 1°C rise in average growing season temperature over the study period. On average, there was a 5.3% reduction in yield for each 1°C rise in average growing season temperature across the six shires. Other studies have generally used simulation programs such as APSIM to probe the effects of increase temperature or reduced rainfall. However, different experimental setups do not always make it easy to compare results.

Asseng *et al.* (2011) used APSIM to calculate the variation in grain yield versus the number of days > 34°C (anthesis to maturity) at various locations in Australia, including Wagga Wagga. Using their figures, each extra day over 34°C equated to an approximate 0.64°C rise in average growing season maximum temperature. Relating this to their yield versus days > 34°C results indicates an approximately 7% reduction in yield for each 1°C rise in average growing season maximum temperature across Australia, the yield reduction being possibly less in Wagga Wagga (individual location percentages were not reported).

Wang *et al.*(2009) using climate records from 1889-2006 from Wagga Wagga and APSIM to simulate a range increases in average temperature. For each 1°C increase there was a 10% average reduction in yield for the wheat variety Hartog and 7% reduction for Janz, giving an average reduction of 8.5%. The time series model for Wagga Wagga in the current study indicated an average 4.4% yield reduction for each 1°C increase in temperature. However, Wang *et al.* (2009) cautioned that the high level of N application in their APSIM simulations may have led to an increased yield reduction in dry years due to the depletion of water by early growth.

Another analysis was done by Luo and Kathuria (2013) encompassing the NSW wheat growing shires of Moree, Narrabri, Gilgandra, Lachlan, Carrathool and Bland. This is a similar cross section to that of the current study, but covering more of the northern part of the NSW. APSIM (5.0) was used and included two soil types and the wheat cultivars Sunvale and Janz. Analysis of their data indicated an approximate 4% yield decrease for each 1°C increase in average growing season temperature averaged across the five shires in their study. This compares with the 5.3% reduction result from the time series model for the six shires in SD150 in this study.

Chapter 4 – Use of both time series and the APSIM models to simulate an increase in temperature and decrease in rainfall in a wheat cropping area of southern NSW

4.1 Introduction

In the previous study (Chapter 3) a time series model was trained using weather station records and wheat yields from six shires in southern NSW. These shires together comprise the main wheat growing areas of Statistical Division 150 (SD150). The training used shire wheat yields from 1922-1994 (Fitzsimmons, 2004). This model was then validated using a later set (1982-2008) of wheat yield figures supplied by ABARE. The times series predictions were then compared with the APSIM simulation predictions based on the same weather station records.

Computer based models can be validated against existing weather and yield records, as was done in Chapter 3, but if predictions are to be made using weather records that exceed the averages and extremes of the validation data, then this introduces a degree of uncertainty. To remove some of the uncertainty the model should be tested against field experimental data before extrapolation is attempted (Asseng *et al.*, 2004; Asseng *et al.*, 1998; Loomis *et al.*, 1979). Thus a consideration for simulation models, such as APSIM, is whether their processes correctly capture the effects of extreme stress, beyond what may have been experimentally tested in the field.

APSIM-Wheat (V7.5) inputs the daily maximum and minimum temperature to calculate wheat growth processes such as photosynthesis, leaf area and senescence (Asseng *et al.*, 2013). Growth stages are determined by a daily thermal time (DTT) calculation. DTT depends on a three hourly mean temperature calculation multiplied by a factor that has an optimum value at 26°C and decreases linearly to zero at either 0°C or 34°C (Wang and Zhao, 2013). Leaf growth and senescence are controlled by a trapezoid function. Leaf area growth reduces if the daily mean temperature is less than 11°C or greater than 24°C (Asseng *et al.*, 2013). However, if the temperature exceeds 34°C then there is a rapid acceleration of leaf senescence (Asseng *et al.*, 2013). Wang and Zhao (2013) questioned whether the trend lines between the base, optimum and maximum temperatures, for calculations such as radiation use efficiency, should be linear. They suggested that these trends should follow a curvilinear path. In a simulation program such as APSIM, not all environmental variables can be practically included in the input. However, Luo and Kathuria (2013) claim that temperature, solar radiation and rainfall are modelled by APSIM, but humidity, which can constrain canopy cooling at high temperatures (Lobell, 2013), is ignored.

As outlined in the previous chapter, the effects of heat on wheat yield are related to both the degree of heat and the stage of development of the wheat plant. Therefore optimum temperatures should be chosen that are relevant to the growth stage. Although the reproductive stage is considered the weakest link in the susceptibility of wheat to high temperatures (Porter and Semenov, 2005; Saini and Aspinall, 1982; Zinn *et al.*, 2010), APSIM does not model the detrimental effects of high temperature on reproductive organs such as pollen (Lobell *et al.*, 2013). For ecophysiological models in general, some reviewers (Fischer, 2011; White and Hoogenboom, 2010) feel that the effect of heat stress is an area that is in need of further research and model development.

Other factors that can affect the accuracy of predictions, when variables are beyond the validated range, include non-additiveness of model effects and how input parameters can interact in different ways depending on the input range. An example of non-additiveness is the effects of heat stress and drought. The combined effect of these two variables on wheat yields is not equal to the sum of the individual effects (Shah and Paulsen, 2003). Similarly, Grigirova *et al.* (2011) found that, in the expression of heat shock proteins, the effect of separately applied heat shock and drought could not be extrapolated to the combined effect. Sensitivity tests on models such as APSIM can reveal interactions between parameters. The extent of yield variations as a result of increased temperatures is determined by other factors such as biomass accumulation, flowering time, and vapour pressure deficit. If only limited field experiments have been carried out to validate the extent of these interactions, then the qualitative value of predictions by the model should be treated with caution (Asseng *et al.*, 2004).

Thus there is a degree of uncertainty, when conducting a sensitivity analysis of a model, commensurate with the degree of validation by field experiments. The confidence in yield predictions where climate change scenarios are used, such as increased temperature and decreased rainfall, is lessened to some extent by suggestions given by Luo and Kathuria (2013) that there are limitations in the APSIM-Wheat model when doing this type of study and that the existing APSIM-Wheat model is in need of improvement. Therefore, this study aims to conduct sensitivity analyses of the APSIM simulations compared with simulations produced by the time series models described in Chapter 3 in response to changes in temperature and/or rainfall. Differences in the simulated changes in yield in response to temperature and/or rainfall changes, across the six shires in the study, should be a useful method of evaluating the performance of APSIM climate change predictions.

4.1.1 **Research question**

- Do the time series model and APSIM provide similar simulations when predicting wheat yields resulting from a 1°C rise in temperature, or a 10% decline in growing season rainfall, or a combination of both?

4.2 **Methods**

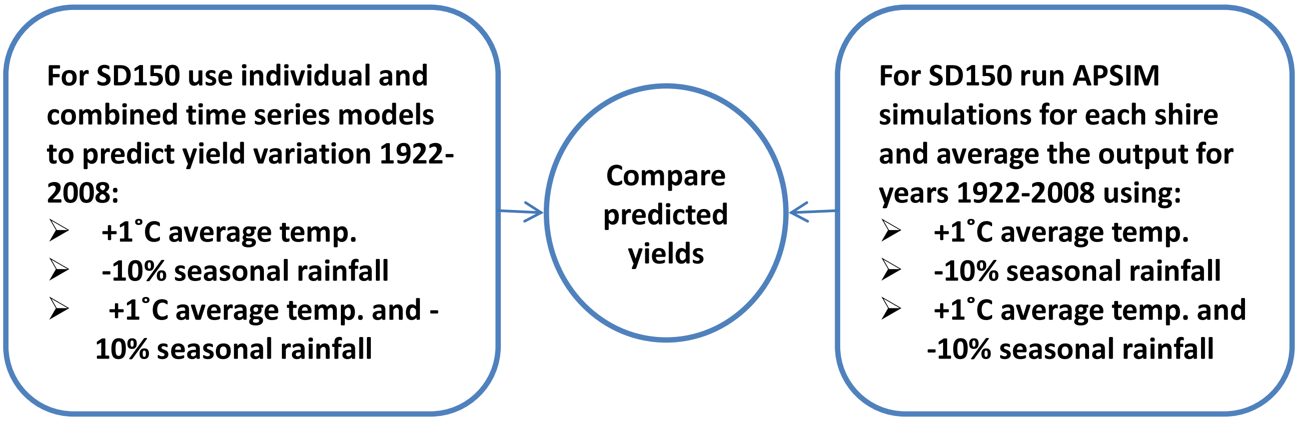


Figure 4-1: Overview of method used to compare temperature and rainfall variation predictions from the time series model and the APSIM simulations for SD150 for the years 1922-2008.

4.2.1 **Area selection**

The area selected is the same as used in the Chapter 3 study. It comprises six shires in southern NSW (Carrathool, Narrandera, Coolamon, Temora, Lockhart and Wagga Wagga) which together constitute the major wheat cropping areas of Statistical Division 150 (SD150). These shires were chosen because of the consistency of their cropped area over the study period (1922-1994). SD150 was chosen because a) it encompassed these six shires and b) there was a yield dataset that covered this area for a later time frame (1982-2008). This dataset was useful for validation of the time series model built using the earlier shire level data. For a map of the areas selected see Figure 3-2 and Figure 3-3.

4.2.2 **Yield datasets**

The yield datasets were described in Chapter 3. They included wheat yields for Australian Statistical Divisions from 1982 to 2008, obtained from ABARE, courtesy of James Walcott, Senior Scientist, Mitigation and Adaptation Sciences, and wheat yield data covering New South Wales (NSW) shires for the years 1922-1994 from the book prepared by Fitzsimmons (2004).

4.2.3 **Weather data**

Weather stations were selected such that they were evenly spaced across the six shires (Chapter 3, Figure 3-3). Weather station data was obtained from the Queensland Government Specialised Information for Land Owners (SILO) climate database (http://www.longpaddock.qld.gov.au/silo). The methods used to extract the relevant weather variables and produce new calculated variables are also described in Chapter 3. This included high degree hours (HDH) and growing season rainfall variables, both used in the multiple regression analysis to produce the time series models.

4.2.4 **Sensitivity analyses**

Time series

In Chapter 3, for each of the shires of Carrathool, Narrandera, Coolamon, Lockhart and Wagga Wagga and the combined shires (SD150), a time series model was constructed using detrended shire wheat yields and the weather station records for the years 1922-1994 using the relationship:

Yield Delta% = RF% + HDH

where RF% is the growing season rainfall deviation from average as a percentage and HDH is the high degree hours. A time series model was also built for the combined shires, which together represent the main wheat growing areas of SD150. To simulate a 1°C rise in average growing season temperature for the period 1922-2008, the daily minimum and maximum temperatures were incremented by 1˚C. HDH was then recalculated for each day of the study period. To simulate a 10% decrease in average growing season rainfall, the total growing season rainfall for each year was multiplied by 0.9 and the result expressed as a percentage change (RF%) from the average growing season rainfall for the years 1922-2008. Yearly yield predictions were then calculated for each of the models and their associated areas.

APSIM

The "climate control" component of APSIM allows the perturbation of temperature by a constant amount and rainfall by a percentage amount. For example daily maximum temperature can be incremented by 1°C and the daily rainfall by a negative 10%.

As in Chapter 3, the APSIM template 'Continuous Wheat Simulation' was used. Climate control options were selected for change in maximum temperature 1°C, change in minimum temperature 1°C, relative change in daily rainfall 0%, then change in maximum temperature 0°C, change in minimum temperature 0°C, relative change in daily rainfall -10% and finally change in maximum temperature 1°C, change in minimum temperature 1°C, relative change in daily rainfall -10%. All other APSIM options were the same as those outlined in Chapter 3. Simulations were run for each of the six shires using the soils and weather station records shown in Chapter 3, Table 3-8, for the years 1922-2008.

4.2.5 **Statistical analysis**

The response of the APSIM simulation predictions to a rise in average temperature of 1°C were analysed by comparing the annual yield predictions before and after the 1°C rise. How APSIM deals with HDH increases was also analysed by comparing the yearly higher HDH values (resulting from the simulated temperature rise) with the yearly yield prediction variations.

The yield predictions of the time series model and APSIM were averaged over the years 1922-2008 and compared graphically between shires and by treatment for the combined shires, which together comprise SD150.

The coefficient of correlation (r) between the yearly predictions of each model (APSIM and time series) for each area (shires and SD150) and category (+1°C temp.; -10% rainfall; 1°C temp. and -10% rainfall) were also calculated.

Although the time series model (Chapter 3) was built by excluding years where rainfall was greater than 30% above average (this was so that a linear term for rainfall could be used in the model equation), the simulations were based on the weather records for all years (1922-2008). The justification for this was that heat and low rainfall effects, do not normally occur in years of above 30% average rainfall. As a check, the yield predictions were also calculated excluding years of greater than 30% of average rainfall for all shires (results not shown). There was less than a 1% difference in model outputs in almost all cases.

4.3 **Results**

Table 4-1. For six shires in SD150 in southern NSW the initial average high degree hours (HDH) calculated over the period 1922-1994 and the resultant rise in average HDH when the daily minimum and maximum temperatures are raised by 1°C.

Shire	Initial HDH	Final HDH	Increment
Carrathool	152	239	87
Narrandera	91	149	58
Coolamon	53	92	39
Temora	45	79	34
Lockhart	38	66	28
Wagga Wagga	36	64	28

The north western shires, such as Carrathool, have a higher level of average HDH than the south eastern shires, such as Wagga Wagga (Table 4-1). When a 1°C rise in average temperature was simulated by incrementing the existing temperature record, the resultant increase in HDH was also higher in the north western shires. Thus, although the time series regression equation for Carrathool (Appendix C Table A-3) has a smaller coefficient for HDH than the equation for Wagga Wagga, the effect of a 1°C increase in Carrathool actually has a larger effect due to the greater than threefold increase in average HDH increment at Carrathool (87) compared with Wagga Wagga (28).

For the APSIM simulation yield predictions, the results of a 1°C rise in average temperature were far from uniform across shires or from year to year (Figure 4-2). For the time series models, rainfall (up to 30% above average) had a positive effect while the effect of HDH was always negative (Table 3-9). This was not the case with APSIM; where other factors such as rainfall distribution, interact with periods of high temperatures making the year to year outputs quite variable. Increased temperature (i.e., + 1°C) in many years resulted in higher yield predictions. Surprisingly this was more pronounced in the drier shire of Carrathool than in cooler and wetter Temora shire (Figure 3-9). Some consecutive years showed large yield changes as a result of the 1°C temperature rise, for example Coolamon experienced a 2.9 t/ha yield reduction in 1939 followed by a 1.7 t/ha increase the following year. Thus, although both modelling methods give similar results, the APSIM simulations show more year to year sensitivity to rainfall and heat distribution than the time series model, which only uses growing season rainfall and reproductive stage heat episodes to produce its yield predictions.

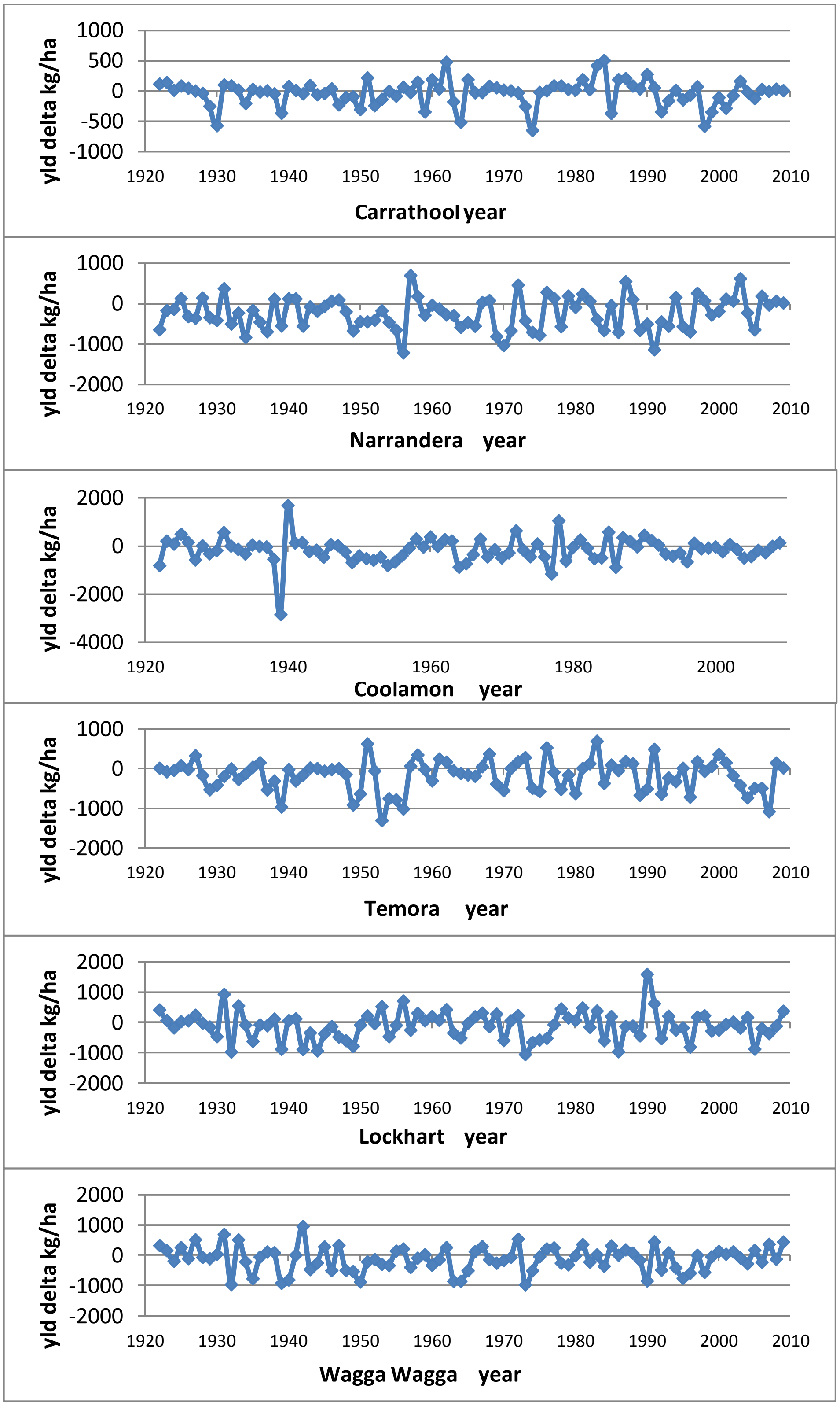


Figure 4-2. For the APSIM simulation, predicted yield variations when the average temperature is raised by +1°C for the years 1922-2008 for the six shires in SD150. For some shires the 1°C rise causes surprisingly large yield fluctuations, for example the year 1939 in Coolamon.

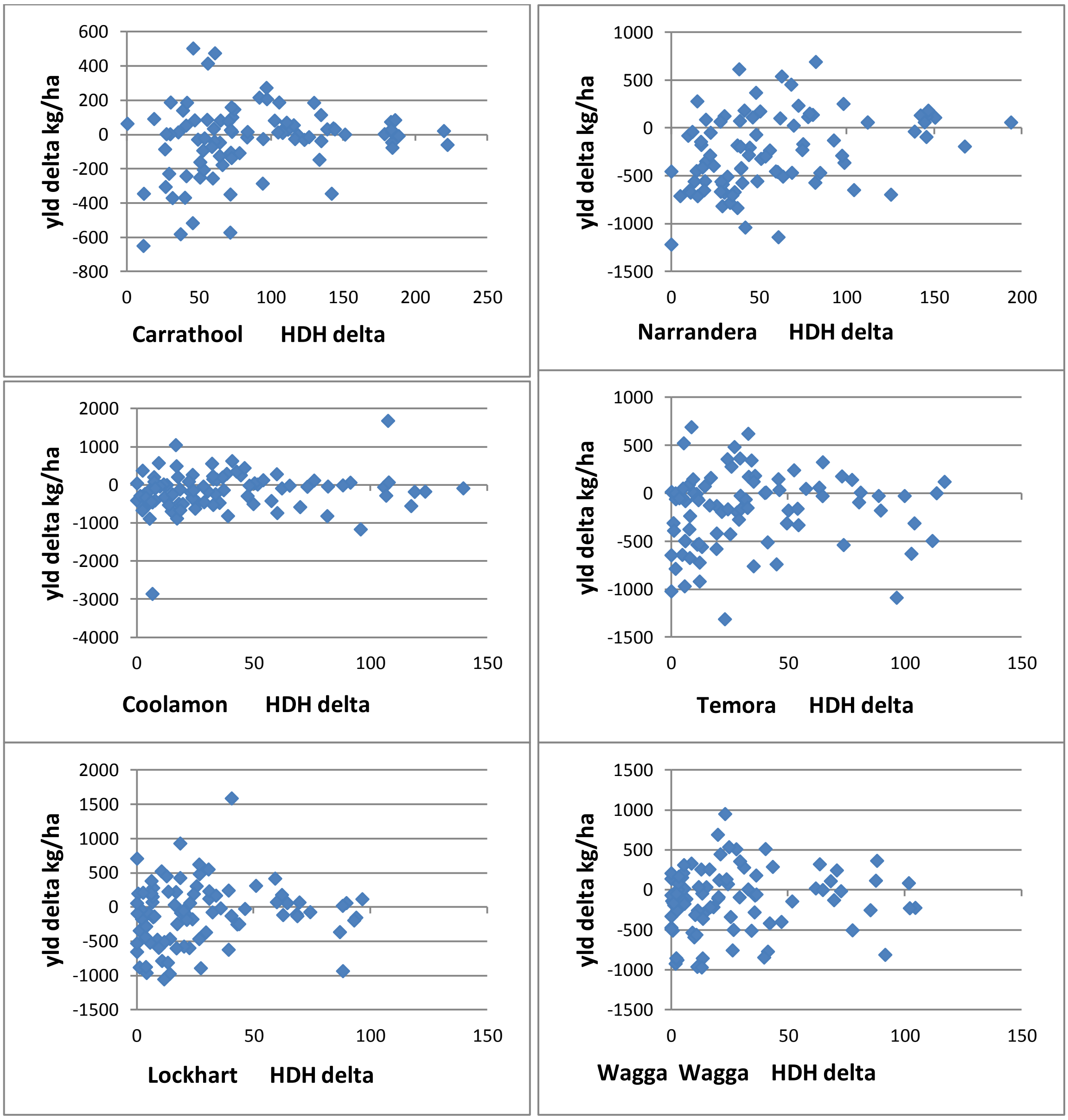


Figure 4-3. For the APSIM +1°C simulation, predicted yield variations are compared to HDH delta (1922-2008) for the six shires in SD150. For all shires there appears to be little relationship between higher HDH values and the predicted yield variations.

When yearly yield variations were compared with the increases in HDH in each shire (that resulted from a 1°C temperature rise), there seemed to be little relationship between the HDH increments and the yield variations in any of the shires (Figure 4-3).

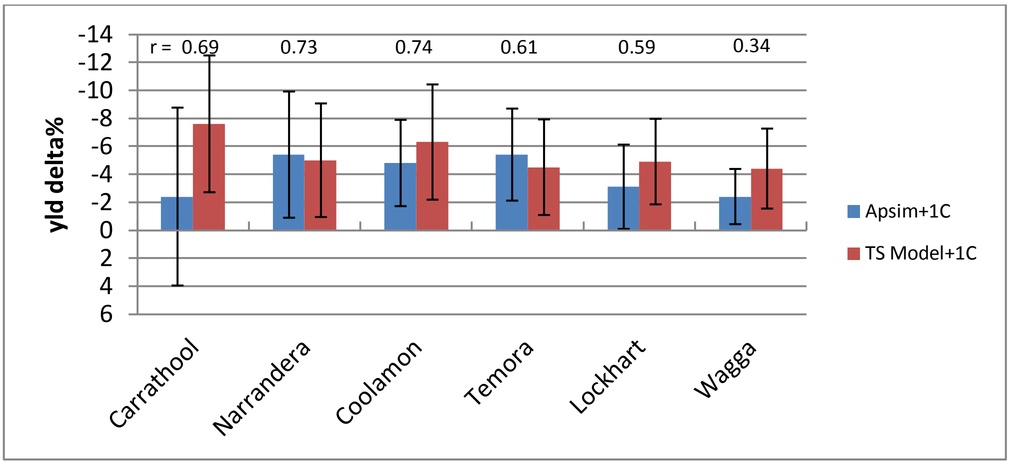


Figure 4-4. For shires in SD150, a comparison of the APSIM and time series model average predicted yield percentage changes from actual historical yields for a +1°C growing season maximum and minimum temperatures 1922-2008. Error bars are standard error of the mean. R values are the coefficient of correlation between the APSIM and time series model yearly predictions for each shire.

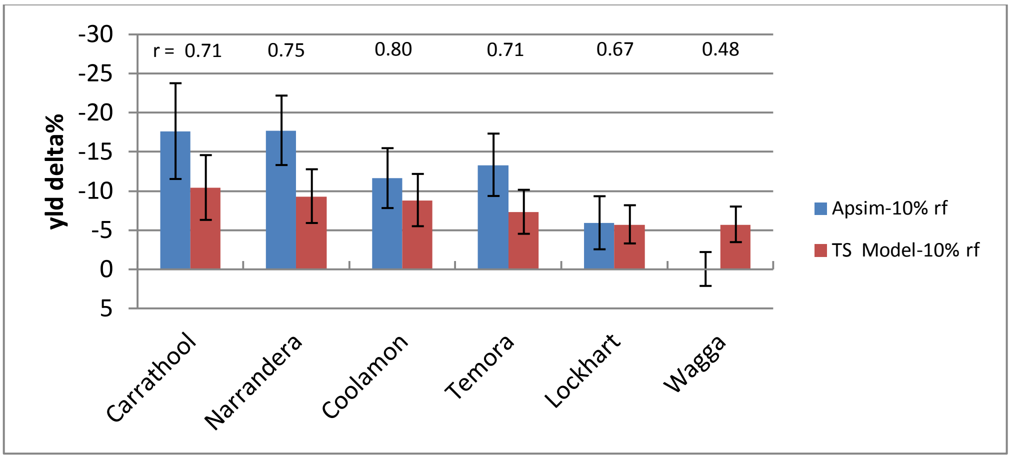


Figure 4-5. For shires in SD150, a comparison of the APSIM and time series model average predicted yield percentage changes from actual historical yields for a 10% decrease growing season rainfall 1922-2008. Error bars are standard error of the mean. R values are the coefficient of correlation between the APSIM and time series model yearly predictions for each shire.

The outputs of the sensitivity analysis of the APSIM and time series models were qualitatively similar across the six shires, both for a 1°C rise in temperature (Figure 4-4) and for a 10% reduction in growing season rainfall (Figure 4-5). However, the time series model in general predicted greater yield reductions than APSIM for a 1°C temperature rise, while APSIM, in four out of six shires, predicted higher yield reductions when there was a 10% rainfall reduction. There was a large amount of variability (indicated by the error bars) in some of the predictions, most notable in the north western shires, especially with the 1°C temperature rise predictions. When the simulations were run with combined conditions of 1°C temperature rise and 10% rainfall reduction, the APSIM and time series model predictions were closer (Figure 4-6).

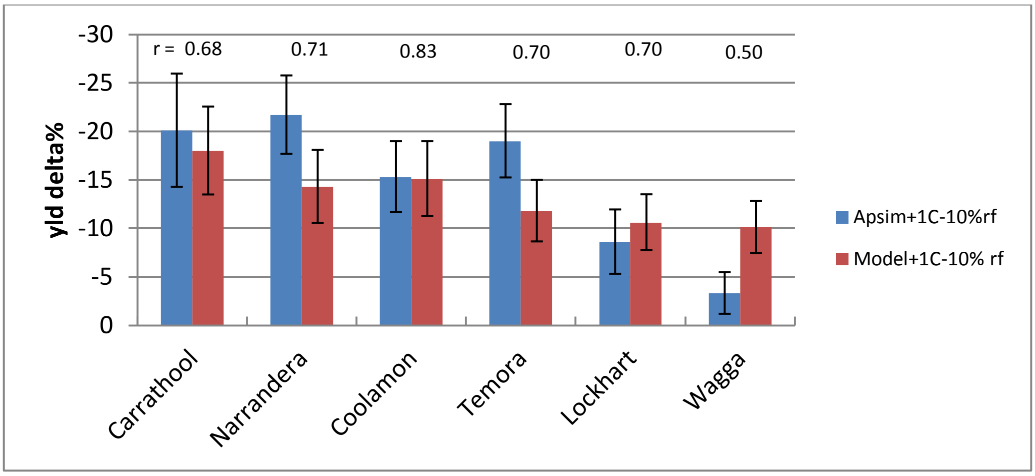


Figure 4-6. For shires in SD150, a comparison of the APSIM and time series model average predicted yield percentage changes from actual historical yields for a +1°C growing season maximum and minimum temperatures and a 10% decrease in average growing season rainfall 1922-2008. Error bars are standard error of the mean. R values are the coefficient of correlation between the APSIM and time series model yearly predictions for each shire.

The combined shires (which comprise SD150) APSIM and time series model predictions (Figure 4-7) produced qualitatively similar outputs. Again the time series model predicted higher yield losses than APSIM for a 1°C temperature rise while APSIM predicted higher yield losses than the time series model for a 10% rainfall reduction.

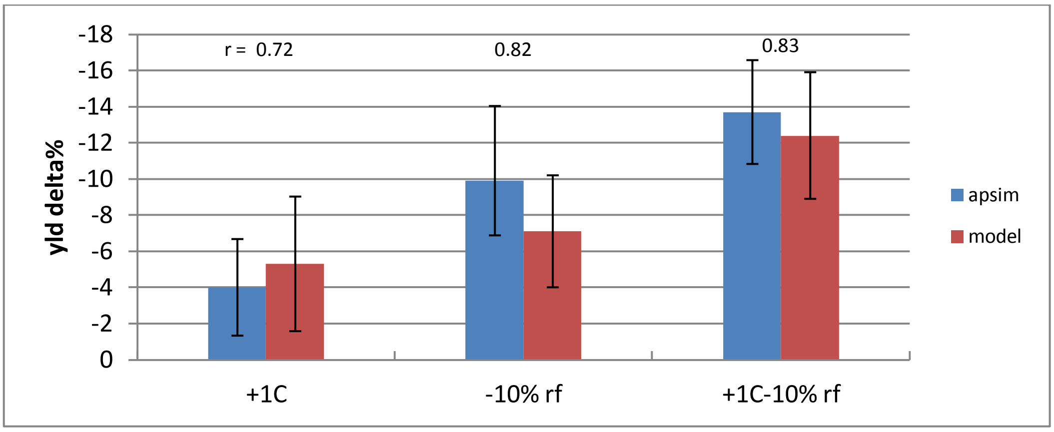


Figure 4-7. For SD150, a comparison of the APSIM and time series model average predicted yield percentage changes from actual historical yields for a +1°C growing season maximum and minimum temperatures, a 10% decrease in average growing season rainfall, and a combination of both, 1922-2008. Error bars are standard error of the mean. R values are the coefficient of correlation between the APSIM and time series model yearly predictions for each category.

4.4 Discussion

From this study APSIM did not predict lower yields directly as a result of increased HDH. Part of the reason may be due to the way APSIM handles heat stress. The main temperature effects modelled by APSIM are rates of leaf senescence, biomass accumulation and its subsequent partitioning into stem, roots and leaves. At the reproductive stage, accumulated stem and leaf weight are used to determine grain number. Thus heat episodes may have a delayed effect on grain number determination due to factors such as a shortened vegetative growth stage and increased leaf senescence. It is possible that these negative effects may be countered during the simulation by other periods of favourable growth. However, heat episodes (i.e. HDH) that damage reproductive organs or processes would have an immediate and non-reversible effect on subsequent yields. The fact that APSIM did not model this damage may explain why HDH does not appear to be important in its yield predictions, whereas in the time series modelling it was identified as the main negative factor.

For the shires, there is a reasonable correlation between the time series and the APSIM model yearly predictions in all areas except Wagga Wagga. This may be because yields are predominantly driven by rainfall in most of the drier regions, while Wagga Wagga, having a higher rainfall, is influenced to a greater extent by other variables, such as rainfall distribution, that are not included in the time series model. With both models yield losses are generally greatest in the drier/hotter north western shires for both the 1°C temperature rise and 10% rainfall reduction scenarios. These yield losses reduce almost linearly as rainfall average rainfall increases and temperatures become cooler in the more south eastern shires. The APSIM simulation predicts greater losses for the 10% rainfall reduction than the time series model, while the reverse situation occurs for the 1°C temperature rise. When the two conditions are combined the predictions of the two models are quite close, both for the individual shires and the combined shires area (SD150). The study by Yu *et al.* (2013) had similar conclusions. They statistically evaluated historical wheat yields in Queensland and compared these data with the APSIM simulation predictions. Their finding was that APSIM provided good estimates of wheat yields under normal rainfall conditions but underestimated yields in low rainfall situations. If the 10% rainfall reduction in the current study is treated as analogous to the low rainfall statistical grouping in the Yu *et al.* (2013) study, then the findings of the two studies are similar in at least this respect.

Since APSIM did not appear to directly model the HDH damage to reproductive processes, its predictions are more influenced by rainfall and its interaction with increased temperatures, whereas the time series model directly models the effect of HDH and reflects this in its higher yield loss predictions for 1°C temperature rise. In reality higher HDH and reduced rainfall are closely correlated (Chapter 3, Figure 3-9) and the emphasis that is seen on either temperature change or rainfall change in the predictions of each model are under conditions that would not occur naturally. The time series model was built using observed weather and yields, and APSIM has also, to a large extent, been fine-tuned and validated using observed yields and weather. Although the sensitivity analyses for the two models do produced reasonably similar model outputs, field experimental data, with controlled temperature and rainfall changes, would further elucidate which model has the correct emphasis.

Chapter 5 - Testing selected wheat varieties for heat tolerance in the greenhouse and the field

5.1 Introduction

Heat stress is a problem for Australian wheat crops. During the reproductive stage, when heat stress is most damaging to wheat (Porter and Semenov, 2005; Saini and Aspinall, 1982; Zinn *et al.*, 2010), wheat crops in many parts of Australia regularly experience episodes of temperatures that are above the optimal levels as defined by Farooq *et al.* (2011). In Chapter 3, the southern NSW shire of Carrathool suffered an average 15% yield reduction over the period 1922-1994 as a result of high degree hours occurring during the reproductive stage.

Australia's climate is expected to become warmer and drier in coming decades. Projections based on the Intergovernmental Panel on Climate Change (IPCC) A1B business as usual scenario (Solomon *et al.*, 2007; Tebaldi and Knutti, 2010) indicate that temperatures may be on average 2.6ºC higher in southern Australia by 2050. In addition there is a projected increase in the number of days exceeding 35ºC and 40ºC in the spring and summer months respectively (Tebaldi and Knutti, 2010). Increases in average temperatures and climate variability are likely to have a negative effect on wheat yields in south-eastern Australia (Anwar *et al.*, 2007) and South Australia (Luo *et al.*, 2010), while an increase in the number of days > 34ºC during grain filling is predicted to generally reduce wheat yields throughout the wheat growing areas in Australia (Asseng *et al.*, 2011). Thus, the challenge for the wheat breeder is to produce new varieties that are better suited to current and future climatic stresses. This is even more important in Australia where most wheat crops are rainfed and already subjected to varying degrees of damage from both drought and heat.

The aim of the study described in this chapter is to identify heat tolerant germplasm that may be useful in breeding programs to enhance high-temperature tolerance in Australian bread wheat.

New breeding line and synthetic cultivars

For plant breeders an important pre-condition is to obtain germplasm with genetic variability. Sources can be found within existing varieties, but more genetic variability is available by utilising germplasm from ancestral varieties. Bread wheat is a hexaploid that may have arisen 8000-9000 years ago, following chromosome doubling, from a cross between tetraploid *Triticum dicoccum* (emmer wheat) and diploid *Aegilops tauschii* (goat grass) (Trethowan *et al.*, 2010). Current hexaploid wheats may have a restricted gene pool, especially in relation to tolerance of abiotic stresses, because of a founder effect in the early crossings (Gororo *et al.*, 2002). Accessions of *Aegilops tauschii* collected worldwide still have better tolerance of heat and drought than modern hexaploid wheats. New primary synthetic hexaploid wheats have been produced by crossing *Aegilops tauschii* with *Triticum durum*, a tetraploid. These primary synthetics were then crossed to modern agronomically superior hexaploid wheats, in an effort to incorporate the genes for increased tolerance of abiotic stresses, without losing the yield and other important qualities of modern wheats (Trethowan and Mujeeb-Kazi, 2008).

One of the wheat breeders aims when producing new cultivars, such as synthetics, is that they have superior yield performance in target environments. An important consideration is to what degree the expression of a trait such as heat tolerance, is environment specific (Trethowan *et al.*, 2010). Evaluation of experimental designs should therefore take this into account. For example, plants may react differently to moisture stress depending on whether they have the ability to resist or tolerate heat. Heat resistance enables the plant to avoid damage to tissues by preventing the entry of heat and the effectiveness of this mechanism can be dependent on soil moisture levels. High temperature tolerance is the ability of tissues to survive even when heat penetrates to the internal tissues of the plant (Acquaah, 2007). Monitoring physiological mechanisms such as leaf conductance and/or canopy temperature during evaluation experiments can help determine which of these mechanisms are at work (Reynolds *et al.*, 2009).

Small scale experiments are a first step in the evaluation of new cultivars in a target environment. The size of the experiment may be dictated by seed availability and the capacity of greenhouses and/or managed environment facilities. Experiments carried out in a controlled environment are an opportunity to further characterise the heat tolerance of new cultivars and to compare their performance with that of currently grown local varieties. A controlled environment also allows aspects of the target environment to be mimicked. A greenhouse and heat chamber can be used to apply temperature extremes at plant growth stages, such as flowering, while holding other environmental factors constant. Irrigated field experiments using normal and late sowings can provide conditions closer to that of the target environment while providing a regime of higher temperatures for the late sowings. Variety and cultivar are often used interchangeably in the literature, therefore, for simplicity, all wheat lines are referred to as varieties in the remaining sections of this study.

5.1.1 **Research question**

- Are selected overseas wheat research lines more heat-tolerant than current Australian varieties?
- Is the relationship consistent across different experimental environments?

5.2 **Methods**

Ten varieties of wheat were selected for heat tolerance testing. The selection contained a mixture of overseas and locally grown varieties (Table 5-1). Some of the overseas varieties, such as SOKOLL and FILIN, are experimental lines that have been bred for improved tolerance of abiotic stresses such as heat and drought. In this study the aim was to evaluate heat tolerance only. Therefore all plants in each of the experiments received adequate irrigation to ensure there was little or no moisture stress during all developmental stages. The experiments were carried out in the greenhouse in the Darlington campus of the University of Sydney in 2011 and in the field at the Plant Breeding Institute (PBI) Grains Research Institute at Narrabri in 2011 and 2012. Table 5-2 is an overview the experimental setups.

Table 5-1. Overseas and Australian wheat varieties selected for a side by side comparison to determine their relative levels of heat tolerance.

Wheat variety	Varieties thought to have heat tolerance	Origin
CRUSADER	no	Australia
BERKUT	no	Mexico
EGA GREGORY	no	Australia
LIVINGSTON	no	Australia
PBW 343	yes	India
WH 542	yes	India
SOKOLL	yes	Mexico (synthetic)
N-ABYAD-13	yes	India
ZAKIA-10	yes	India
FILIN	yes	Mexico (synthetic)

Table 5-2. Summary of the experimental design of the three wheat experiments using the same 10 varieties for Darlington greenhouse in Sydney 2011, Narrabri field 2011 and Narrabri field 2012.

Experiment/year	Sowing dates	Growing medium	Irrigation	Heat treatment	Layout
Greenhouse 2011	10th June	20 cm black pots with commercial potting mix	yes	26-38°C for 4 days at anthesis	Completely randomised design 3 replicates control, 6 replicates heat
	10th June	20 cm black pots with peat and sand mix	yes	26-38°C for 4 days at anthesis	Completely randomised design 3 replicates control, 6 replicates heat
Narrabri 2011	20th May 1st July	Field	yes	By sowing date	Alpha-lattice design with 3 replicates
Narrabri 2012	14th May 21st June 15th August	Field	yes	By sowing date	Alpha-lattice design with 2 replicates

5.2.1 Greenhouse - Darlington Campus, University of Sydney

The seeds of the ten selected wheat varieties were sown on the 10th of June, 2011, in the Darlington greenhouse into 20 cm diameter pots, five seeds to a pot, at a depth of 1.5 cm. One half of the pots contained a commercial potting mix. The other half contained a sand and peat soil mixture (6 parts peat to 4 parts sand) with approximately 10 g/L of lime and 10 g/L of Osmocote controlled release (NPK18:6:12) fertiliser added. For each variety there were three control pots and six treatment pots. The varieties were randomly allocated across the greenhouse benches to minimise local temperature and light effects. Temperature was controlled to a maximum of 25°C within the greenhouse. Best practice agronomic pest control, fertilising and weeding were carried out as required.

When each treatment variety reached 50% anthesis they were transferred to a heat chamber. The temperature within the heat chamber was controlled to a maximum of approximately 38°C during the day and dropped to approximately 26°C during the night. After four days the treatment varieties were transferred back to the greenhouse. Subsequently all plants were cut back to a single plant and stem, so each pot contained only one tiller (main axis) at maturity.

Plants were harvested at the end of October. Seed drying was performed in a thermal oven for at least 48 h prior to counting and weighing.

5.2.2 Narrabri 2011

The same ten varieties were included in field experiments at the Narrabri PBI in 2011. There were two sowing dates, 20th May and the 1st July 2011. Both layouts were alpha-lattice designs with three replicates in four sub-blocks. Irrigation was applied as necessary and weeds were rigorously controlled. The normal (early) sowing date experiment was harvested on 11th November and the late sowing experiment on 19th November. For each variety, the yield per hectare was calculated.

5.2.3 Narrabri 2012

For the 2012 Narrabri PBI field experiments there were three sowing dates: 14th May, 21st June and 15th August, hereafter referred to as the first, second and third planting respectively. As for the previous year the same ten varieties were included in each of the field experiments and irrigation and other normal agronomic measures carried out. The layouts were alpha-lattice designs with two replicates. Harvest of the first, second and third plantings occurred on the 28th October, 9th November and 29th November respectively. For each of the varieties the thousand kernel weight was measured and the yield per hectare calculated.

5.2.4 **Statistical analysis**

The 2011 and 2012 Narrabri field experiments used an alpha-lattice design with three and two replications, respectively. The alpha-lattice design was an appropriate choice because the varieties in this study were part of an ongoing experiment involving a large number of other varieties (Piepho *et al.*, 2006). Yields were analysed as a randomised complete block design using analysis of variance. Analysis of variance (ANOVA) was used to calculate least significant difference (LSD) between varieties.

For the greenhouse pot experiment the percentage change between control and treatment for each wheat variety/potting mix combination was calculated and tested for significance by t-test.

Percentage change in yield of individual varieties was not considered suitable for comparing yields data between greenhouse and field as the severity and timing of the heat treatments in these experiments were quite different. Therefore a stress index was used to compare variety performance across the different experimental locations and years. The index was calculated as:

Stress Index = (Y stress/Y no stress)/(Mean yield stress/Mean yield no stress)

where ‘Y stress’ is the yield of a variety under the current stress, ‘Y no stress’ is the variety yield in the control environment (no stress), ‘Mean yield stress’ is the mean of all varieties under high temperature stress and ‘Mean yield no stress’ is the mean yield of all control varieties.

ANOVA and LSD calculations enabled a comparison of variety yields against experimental location and year and a ranking and significance level to be calculated for each of the varieties in the Narrabri field experiments.

5.3 **Results**

The seed mass per plant was used as a measure of yield in the greenhouse experiments in 2011. The percentage change is a measure of the extent to which yield was reduced by the heat treatment for each variety. The best performers (green highlight), common to both potting mix types, were: WH542, SOKOLL and CRUSADER, while the worst (yellow highlight) were: EGA GREGORY, BERKUT, N-ABYAD-13, ZAKIA-10 and FILIN (Table 5-3).

Table 5-3. Greenhouse (2011): Average total seed mass (g)per plant for controls and heat treated plants using the commercial potting mix (comm.) and for the control and heat treated plants using the peat and sand potting mix (p&s). The change% is the percent change in seed mass between the control and heated treated plants for each variety. '*' indicates the change percentage is significant P<.05 while '' indicates P<0.01.**

Greenhouse yields	mean yield control comm. (g)	Mean yield heat comm. (g)	change% comm.	Mean yield control p&s (g)	mean yield heat p&s (g)	change% p&s
CRUSADER	2.36	1.84	-22%	2.24	1.99	-11%
BERKUT	3.72	0.73	-80%*	3.20	1.22	-62%*
EGA GREGORY	3.09	2.08	-33%**	3.12	2.17	-31%**
LIVINGSTON	3.14	1.98	-37%*	2.36	2.04	-14%
PBW 343	2.97	2.02	-32%**	2.20	2.48	+13%
WH 542	3.11	2.69	-14%	2.97	2.91	-2%
SOKOLL	2.95	2.80	-5%	2.77	2.58	-7%
N-ABYAD-13	3.18	1.56	-51%**	2.89	1.64	-43%*
ZAKIA-10	3.4	1.59	-53%**	3.13	1.51	-52%*
FILIN	3.37	1.97	-42%**	4.42	1.91	-57%*

Seed number is an indicator of how successful the flowering, pollination and fertilisation stages have been and to what extent these stages have been damaged by heat treatment. The data were similar to the seed mass data. The best varieties (green highlight), common to both potting mix types, were: WH542, SOKOLL and CRUSADER, while the worst (yellow highlight) were: BERKUT, N-ABYAD-13, ZAKIA-10 and FILIN (Table 5-4).

Table 5-4. Greenhouse (2011): Average seed number per plant for controls and heat treated plants using the commercial potting mix (comm.) and for the control and heat treated plants using the peat and sand potting mix (p&s). The change% is the percent change in seed number between the control and heated treated plants for each variety. '*' indicates the change percentage is significant P<0.05 '' indicates significance P<0.01.**

Greenhouse variety	mean seed no. Control comm.	mean seed no. Heat comm.	change %	mean seed no. control p&s	mean seed no. heat p&s	change %
CRUSADER	49.7	40.7	-18%	44.0	39.2	-11%
BERKUT	57.3	16.2	-72%**	48.2	23.5	-53%*
EGA GREGORY	51.5	35.3	-32%*	49.9	37.3	-25%*
LIVINGSTON	51.7	39.4	-24%*	41.9	39.8	-5%
PBW 343	49.8	34.4	-31%*	34.0	37.5	+10%
WH 542	66.9	59.5	-11%	49.4	57.7	+17%
SOKOLL	52.7	50.7	-4%	45.2	45.3	0%
N-ABYAD-13	58.0	32.7	-44%**	47.9	29.6	-38%*
ZAKIA-10	63.8	32.2	-53%**	50.1	27.0	-46%*
FILIN	63.8	40.0	-37%**	69.9	36.2	-48%*

In almost all varieties, seed number reduction was accompanied by seed weight reduction, although the percentage reduction was less. The varieties with the largest Thousand Kernel Weight (TKW) reductions were BERKUT, ZAKIA-10 and FILIN while SOKOLL and CRUSADER were again among the top performers (Table 5-5).

Table 5-5. Greenhouse (2011): Average thousand kernel weight (TKW) for controls and heat treated plants using the commercial potting mix (comm.) and the peat and sand potting mix (p&s). The change% is the percent change in seed mass between the control and heated treated plants for each variety. '*' indicates the change percentage is significant P<0.05 while '' indicates significance P<0.01.**

Greenhouse variety	mean TKW control comm. (g)	mean TKW heat comm. (g)	change %	mean TKW control p&s (g)	mean TKW heat p&s (g)	change %
CRUSADER	47.0	45.3	-4%	50.5	50.4	0%
BERKUT	64.5	46.4	-28%**	65.7	54.5	-17%*
EGA GREGORY	60.7	59.2	-2%	62.5	57.5	-8%
LIVINGSTON	62.0	50.5	-19%	56.7	51.4	-9%
PBW 343	59.6	58.9	-1%	65.2	66.0	+1%
WH 542	46.4	45.4	-2%	64.8	50.6	-22%
SOKOLL	56.4	55.4	-2%	61.6	57.4	-7%
N-ABYAD-13	55.0	47.5	-14%	60.0	53.2	-11%
ZAKIA-10	53.1	49.4	-7%	62.2	54.2	-13%*
FILIN	53.1	48.8	-8%	63.3	52.9	-16%**

The second sowing date in 2011 at Narrabri encountered appreciably fewer days over 30°C and 35°C than the third sowing date in 2012 (Figure 5-1). However, the first and second sowing date temperatures in 2011 were comparable with the first and second sowing date temperatures in 2012, apart from the higher number of days >25°C in 2011.

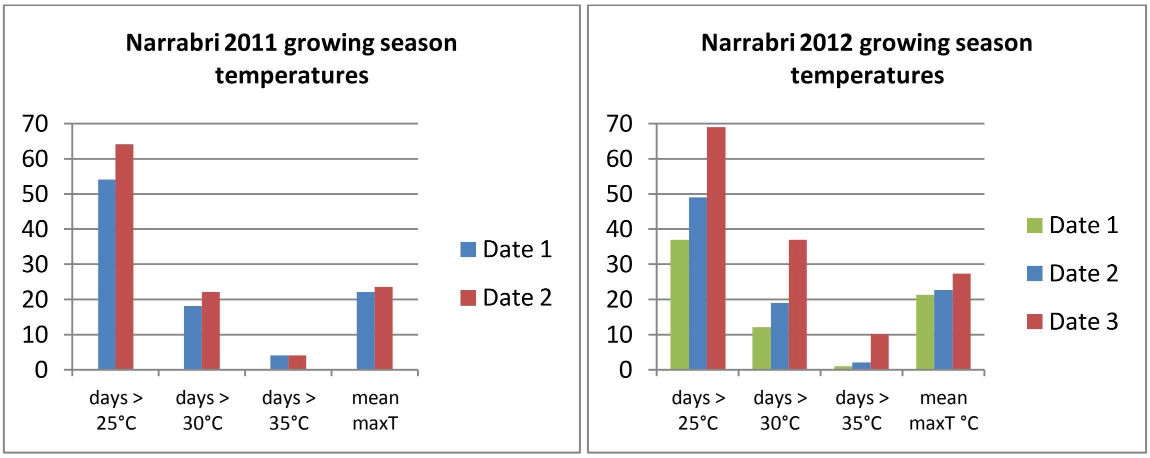


Figure 5-1. A comparison of the temperatures encountered during the growing periods of the wheat experiments at Narrabri in 2011 and 2012. For 2011 the growing periods (sowing to harvest) were: Date 1: 20th May – 11th November and Date 2: 1st July - 19th November. For 2012 the growing periods (sowing to harvest) were: Date 1: 14th May - 28th October, Date 2: 21st June - 9th November and Date 3: 15th August - 29th November.

The percentage change in yield between the normal and late sowing dates is one indicator of heat tolerance (another possibly better measure is the stress index, see Figure 5-3 and Figure 5-4). The 2011 Narrabri data (a cooler season) were almost the reverse of the 2012 Narrabri (a hotter season) (Table 5-6). The putatively heat tolerant varieties, apart from FILN and PBW 343, performed no better or worse than the putatively non-tolerant varieties during 2011 (a cooler season). However, in 2012 all the putatively heat tolerant varieties, apart from WH 542, performed better than the putatively non-tolerant varieties.

The ANOVA of yields for both 2011 and 2012 field experiments (Table 5-7 and Table 5-9) indicate a significant variation between varieties ($P<0.01$) as well as a significant interaction between the varieties and planting dates ($P<0.01$). In 2011, apart from WH 542, the highest yielding varieties also had the lowest percentage decreases (Table 5-8) while in 2012 this situation was somewhat reversed (Table 5-10).

Table 5-6. Mean yields for each of the ten varieties in the 2011 and 2012 Narrabri experiments. Values in brackets () are the percentage change in yield relative to the normal planting(date 1) value. Green highlights are the five best performing varieties for each date (least percentage yield decrease).

	Narrabri 2011 yields		Narrabri 2012 yields		
	Yield date 1 kg/ha	**Yield date 2 kg/ha**	**Yield date 1 kg/ha**	**Yield date 2 kg/ha**	**Yield date 3 kg/ha**
CRUSADER	3800	4217 (+9.8)	3557	2728 (-24.7)	1467 (-62.3)
BERKUT	4315	4063 (-5.9)	4062	2522 (-45.9)	1712 (-70.1)
EGA GREGORY	4423	4056 (-8.6)	3763	2297 (-43.7)	1944 (-54.2)
LIVINGSTON	3915	3171 (-17.5)	3719	2583 (-33.9)	1749 (-58.7)
PBW 343	4388	4590 (+4.8)	3424	3473 (+1.5)	1721 (-50.8)
WH 542	4465	3729 (-17.3)	3856	2787 (-31.9)	1750 (-62.8)
SOKOLL	4371	3338 (-24.3)	3375	2741 (-18.9)	1949 (-42.5)
N-ABYAD-13	4223	3550 (-15.9)	2444	2812 (+11.0)	1147 (-38.7)
ZAKIA-10	4373	3492 (-20.8)	2350	2700 (+10.4)	1266 (-32.3)
FILIN	4173	4210 (+0.9)	2994	2394 (-17.9)	1291 (-50.8)

Table 5-7. Yield Anova for Narrabri experiments in 2011.

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Varieties	3643513	9	404835	3.95	<0.01	2.12
Dates	2435128	1	2435128	23.77	<0.01	4.08
Varieties*Dates	3272438	9	363604	3.55	<0.01	2.12
Residual	4098099	40	102452			

Table 5-8. Narrabri 2011: ranking of the variety mean yields from the two planting dates, LSD=528. Means followed by different letters are different at P=0.05. '*' indicates varieties thought to be heat sensitive. Green highlights are the five varieties that had the least percentage yield decrease relative to the normal planting (date 1).

Variety	*Mean yield kg/ha*	*Significance equivalence*
PBW 343	4489	a
EGA GREGORY*	4240	a
FILIN	4192	a
BERKUT*	4189	a
WH 542	4097	a
CRUSADER*	4009	a
ZAKIA-10	3933	b
N-ABYAD-13	3887	b
SOKOLL	3855	b
LIVINGSTON*	3543	b

Table 5-9. Yield Anova for Narrabri experiments in 2012.

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Varieties	4027656	9	447517	26.37	<0.01	2.21
Dates	30021354	2	15010677	884.55	<0.01	3.32
Varieties*Dates	5581634	18	310091	18.27	<0.01	1.96
Residual	509094	30	16970			

Table 5-10. Narrabri 2012: ranking of the variety mean yields from the three planting dates, LSD=641. Means followed by different letters are different at P=0.05. '*' indicates varieties thought to be heat sensitive. Green highlights are the five varieties that had the least percentage yield decrease relative to the normal planting (date 1).

Variety	*Mean yield kg/ha*	*Significance equivalence*
PBW343	2870	a
WH 542	2798	a
BERKUT*	2765	a
EGA GREGORY*	2646	b
LIVINGSTON*	2621	b
SOKOLL	2589	b
CRUSADER*	2563	b
FILIN	2226	c
N-ABYAD-13	2134	c
ZAKIA-10	2105	c

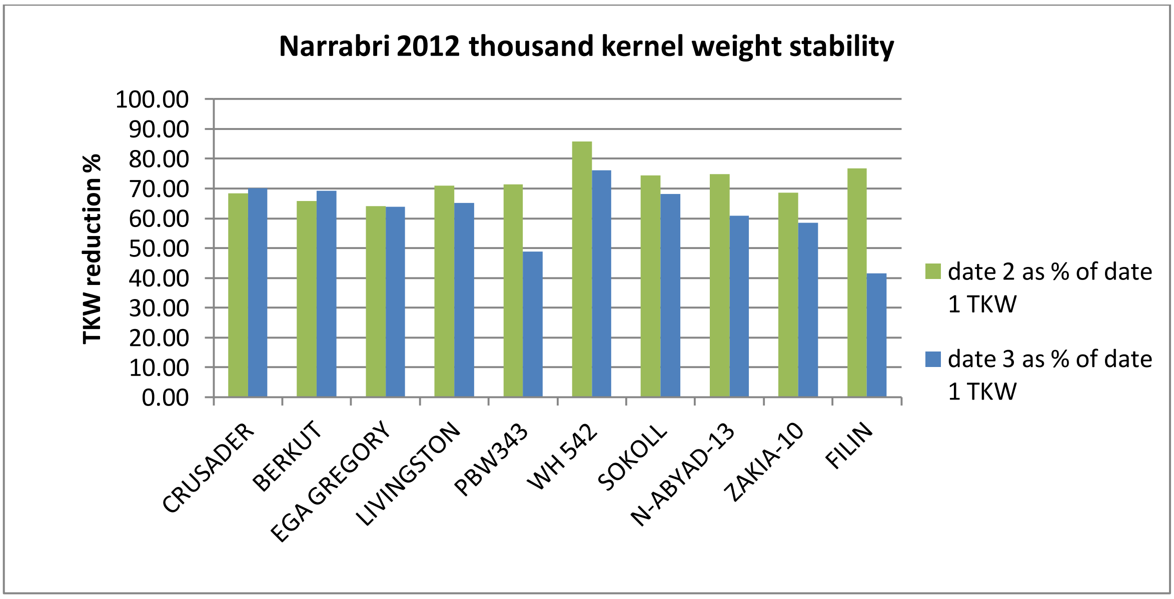


Figure 5-2. A comparison of the percentage reduction in thousand kernel weights (TKW) between dates 1 and 2 (green columns) and dates 1 and 3 (blue columns) for Narrabri in 2012.

The thousand kernel weight (TKW) stability plot (Figure 5-2) is a measure of how well the TKW withstood the higher temperatures of late sowing dates at Narrabri in 2012. The best performer across both dates was WH 542 and then SOKOLL. The worst performer at date 3 was FILIN.

The stress index is a measure of yield resilience of a variety under stress relative to the other varieties in each experiment. Thus, in the current study, a high value indicates a variety had less relative yield reduction under high temperature stress conditions than those varieties with lower values. Figure 5-3 shows that the greenhouse experiments had a higher range of stress values than the field experiments at Narrabri, possibly due to the more extreme temperatures applied at flowering in the greenhouse. The advantage of using a stress index is that yield performance under stress from experiments at different times and locations can be compared.

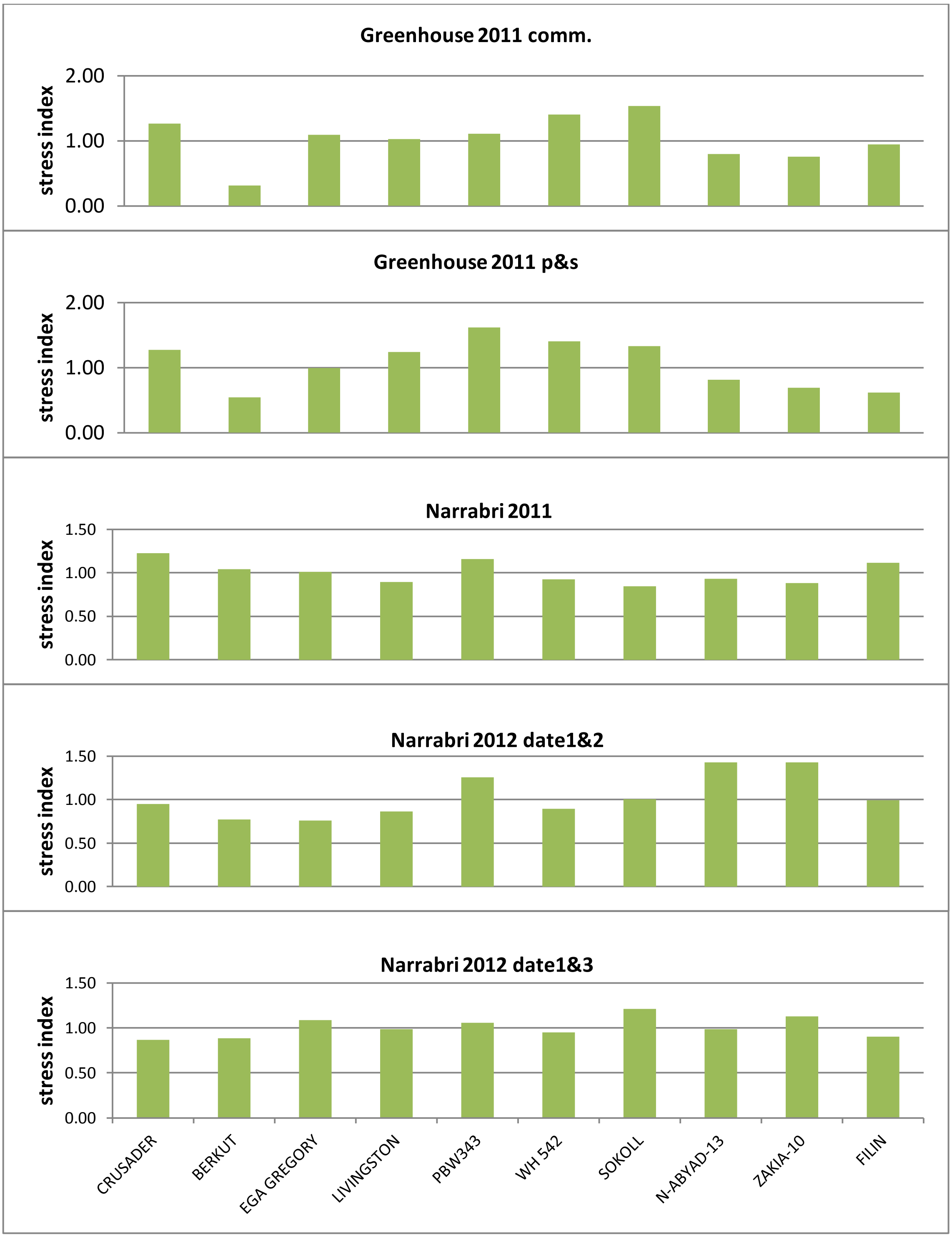


Figure 5-3. Stress index comparison between all years, experiments and varieties (for the greenhouse, comm. is the commercial potting mix, p&s is the peat and sand potting mix).

Comparing the stress indices across all experimental locations and dates (Figure 5-4), the varieties PBW 343, SOKOLL, WH542 and CRUSADER were the best performers overall while BERKUT was the worst performer.

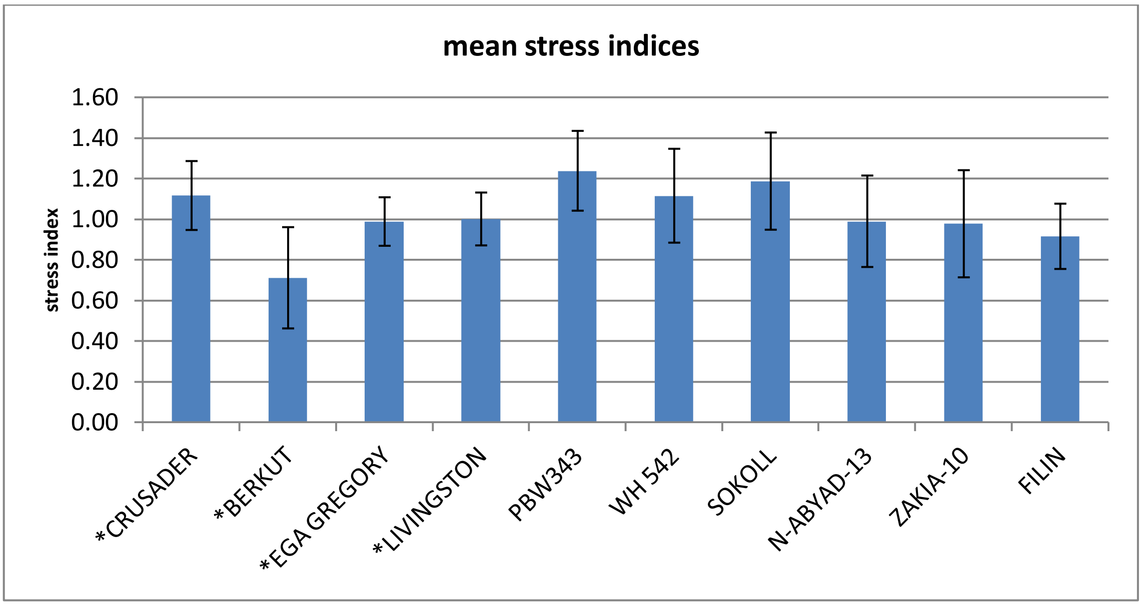


Figure 5-4. A comparison of the mean stress indices across all experiments (Darlington greenhouse, Narrabri field 2011, Narrabri field 2012). A higher index indicates higher heat tolerance. Error bars indicate the 95% confidence interval for each mean. '*' indicates varieties with no putative heat tolerance.

5.4 Discussion

An important goal of advanced selection is to verify the performance of the selected lines over a range of target environments (Brown and Caligari, 2011). After the target environments have been characterised then the required traits for selection need to be identified. For example, when high temperature tolerance is being selected, the requirement may be met by a variety that flowers earlier (avoiding heat), or varieties that have the ability to withstand higher temperatures (tolerating heat). The experimental designs therefore need to address the relevant aspects of heat timing and duration. In this study there were a range of experimental designs and the timing and duration in which heat stress was imposed.

The greenhouse experiments were analysed using a pairwise comparison of yield components between heat treated and control plants in each variety and also by calculating a stress index that could be used for comparison with the Narrabri field experiments. The poorer performing varieties under high temperature stress had the greatest reduction in seed number. This agrees with other studies on the effects of high temperature at flowering (Saini and Aspinall, 1982; Talukder *et al.*, 2010). The best performing varieties had little or no seed reduction. The poorer performers also had the highest reduction in TKW in the greenhouse experiment, which agrees with the findings of Talukder *et al.* (2010) that there is a significant correlation between yield and individual wheat grain mass at maturity.

Comparing heat stress indices across all experiments, there was some consistency, but the diverse seasons, locations and experimental setups introduced a degree of environmental variance that increase the variability of the experimental data when analysed together. The main reason was that the 2011 Narrabri field experiment was conducted during a season that was generally wetter and cooler than normal, thus the normal and late sown field experiments did not encounter the same heat extremes as either the 2012 Narrabri date 3 field experiment or the greenhouse heat chamber experiments. In general the varieties thought to be heat sensitive performed better in the 2011 Narrabri field experiments than the varieties thought to be heat tolerant, but this finding was reversed in the 2012 Narrabri field experiments and to some extent in the greenhouse experiments (the exception was the local variety CRUSADER). The greenhouse and Narrabri 2012 experiment had more temperature extremes than the Narrabri 2011 experiment and varieties such as SOKOLL and WH 542 performed better under these conditions than they did under the milder conditions of Narrabri 2011. Overall, when analysed excluding the 2011 Narrabri field experimental data, SOKOLL, WH 542, PBW343 and CRUSADER were consistently among the top performers. However, this ranking only measures yield reduction under heat stress and does not take into account overall yield performance across all planting dates. In the greenhouse the highest yielding varieties (ranked by control yield) suffered the biggest yield and seed number reduction when heat stressed. This was also the case, to some extent, in the 2012 Narrabri field experiments, but not the 2011 Narrabri field experiments (using mean yield across planting dates). The reason may be to do with the more extreme temperatures and their timing in the greenhouse and 2012 Narrabri experiments. The reduction in TKW was less in the greenhouse experiments compared with the 2012 Narrabri experiments. This indicates the greenhouse yield reductions were related more to reduction in seed number, possibly due to reduced pollen viability, while the yield reductions in the Narrabri experiments were in larger part due to reduced TKW, a known result of heat stress during grain filling (Kaur and Behl, 2010; Talukder *et al.*, 2010; Wardlaw *et al.*, 1989a).

In conclusion, the degree and timing of heat stress is an important consideration when deciding which varieties are superior performers, whether based on field or greenhouse experiments. The decision as to which varieties are superior is therefore contingent upon the type of and degree of heat tolerance being targeted in the breeding program. In the case of these series of experiments, genetic variation for heat tolerance was detected, but its expression was variable with some varieties superior at lower heat levels and others at more extreme levels.

Chapter 6 - General Discussion and Conclusion

6.1 Discussion

In general a problem investigation includes three stages, defining the problem, predicting consequences, and exploring possible resolutions. This research project to some extent has followed that pattern.

The first investigation attempted to establish, from historical records, whether Australian wheat yields have been affected by heat episodes. The second investigation asked a ‘what if’ question in relation to higher average temperatures and/or reduced rainfall. The third investigation then assessed a range of new wheat genotypes for improved high temperature tolerance.

6.1.1 Statistical and APSIM models

The first and second investigations used two modelling methods: an established ecophysiological model (APSIM) and a time series model, built using historical weather and yield records (1922-1994) and validated using a later set of records (1982-2008). For the statistical modeller there are many challenges. One difficulty is interdependence between rainfall and temperature in Australia and how to separate the effects. In this current analysis the most significant factor affecting yields was rainfall and the next most significant, the number of high degree hours (HDH). However, other researchers have built models that ignore one or the other of these factors (i.e. temperature or rainfall). Nicholls (1997) built a statistical model that attributed a large part of historical (1952-1992) wheat yield increases throughout Australia to a decrease in diurnal temperature range (the decrease was mainly the result of an increase in average minimum temperatures over the period). Stephens and Lyons (1998) built a predictive model that relied solely on rainfall, calibrated to different agrometeorological zones throughout Australia. This highlights another point of difficulty in building statistical models; the relationship between rainfall and yields varies across Australia. In most areas, the relationship is positive but in some areas (e.g. south west Australia) the relationship can be negative. The approach therefore, in this project, was to confine the statistical study to a small and reasonably homogenous wheat cropping area in southern NSW. In this selected area rainfall distribution and soils were reasonably similar, although there was a rainfall and temperature gradient across the study area that made it possible to discern trends in the effect of high temperature and rainfall on wheat yields.

The drawback of building and calibrating a statistical model using a restricted set of spatial data is its usefulness in other areas is limited unless re-calibrated. This is where the APSIM model has a greater versatility as it can be more readily parameterised for any area if factors such as soil type and wheat variety are known, but again each individual simulation is for a limited area. An advantage of the statistical model was that it can be readily used to quantify the effect of rainfall and high temperature and it could then be used in a two way check of observed versus statistical and the APSIM model predicted yields. One outcome of this comparison was that a) the statistical model produced more accurate predictions in the study area and b) the APSIM model predictions did not give any indication of having modelled the damaging effects of HDH on the reproductive process. This deficiency in APSIM has been noted by others (Fischer, 2011; White and Hoogenboom, 2010).

Having established there is an ongoing problem with reduced wheat yields due to heat, (e.g. the time series model confirmed an average 15% yield reduction due to high degree hours in Carrathool shire) then a range of possible solutions could be considered. These may include management choices such as switching to new areas, crop types, adding irrigation or possibly sowing at an earlier date (Burke and Lobell, 2010). The other possibility is to assess new wheat varieties for superior heat tolerance, which was the avenue explored in this project.

6.1.2 **Field experiments**

In the field it is not so easy to separate heat tolerance (the degree of heat tissues can withstand without damage) from heat avoidance attributes, such as early flowering, or heat escape mechanisms such as transpirational cooling (Farooq *et al.*, 2011). Therefore testing in the greenhouse, with the only treatment being heat applied at anthesis, should be a means to assess at least one aspect of heat tolerance, i.e. damage to the pollination and fertilisation processes (Ferris *et al.*, 1998). The data supported this hypothesis; the greenhouse experimental data indicated a greater reduction in grain number than in recorded any of the field experiments. On the other hand, in the field (especially in 2012) higher temperatures were experienced later in the reproductive stage and this resulted in reduced yields that were largely due to smaller grain weight. Canopy temperature depression readings would have been an additional method to help separate heat avoidance effects from heat tolerance.

Australia has a wide range of wheat cropping environments and the performance of any new variety has to be assessed as far as possible in conditions that represent the target population of environments. An important aspect of this is the amount of genotype x environment interaction. The data from the Narrabri field experiments indicated $P<0.01$ interactions between the planting dates and the yield performance of the tested varieties and these experiments therefore, can be considered part of a larger testing regime to determine the field performance of these varieties under Australian conditions. This is in accordance with other researchers findings, such as Trethowan *et al.* (2010) and Ogbonnaya *et al.*(2007). When synthetic backcrossed wheat lines (SBLs) from CIMMYT were tested under Australian conditions they outperformed local varieties in northern areas such as Queensland and northern NSW but were less successful in the cooler and winter dominant rainfall southern zones such as Horsham in Victoria. However, Ogbonnaya *et al.*(2007) found that one group of elite SBLs was superior to local varieties in all Australian environments where it was tested.

6.1.3 **Future research considerations**

The time from initial selection of promising new varieties to actual release to the farming community can take as long as ten years and ideally faster assessment methods should be found, especially since climate change may have a significant influence on the viability of currently grown wheat varieties. The current selection processes can include a combination of conceptual models (Reynolds and Trethowan, 2007), simulation models, greenhouse and field experiments. Any one of these methods is a candidate for improvement. For example, there is further experimental work that could be done to determine the cause of grain weight reduction when heat shock is experienced at or soon after anthesis, such as whether it is reduced assimilate supply (following leaf senescence) or possibly soluble starch synthase inhibition during grain development that causes a reduction in grain weight (Fischer, 2011). Trait based selection (Reynolds and Trethowan, 2007) is useful for characterising and identifying promising varieties in early generation selection and pre-breeding experimental evaluation. However, the best progress is made when a trait, such as improved transpiration efficiency, is chosen and is shown to have minimal response to changing environment (Chapman, 2008). The problem, as found in this project (and described by others such as Fischer (2011)) is that heat tolerance is a complex trait and screening can be made difficult by the multiple environmental effects, such as prior hardening (acclimation), soil water supply, vapour pressure deficit and excess heat to the roots when screening container plants (Fischer, 2011). Ideally a series of well controlled field experiments could identify quantitative trait loci (QTLs) for heat tolerance that are valid across a range of environments (Reynolds and Trethowan, 2007), but this is still in progress (Fischer, 2011).

APSIM is useful as a yield prediction tool in most situations, but the data from this project indicated its accuracy could be improved by better modelling of the effects of heat episodes. This agrees with the views of Zhu *et al.* (2011) and Fischer (2011), that APSIM is not as robust when predicting crop performance under environmental extremes. Since APSIM does not explicitly model the effects of spring heat, there is a problem using APSIM to predict yields and analyse genetic x environmental effects.

A further proposed method to improve APSIM is the incorporation of traits and their links to molecular markers and/or QTLs into the model (Chapman, 2008; Fischer, 2011; Reynolds and Trethowan, 2007). Chapman (2008) suggested that APSIM lacks accurate descriptions of the underlying growth mechanisms and interactions of the plant canopy with the environment, and APSIM should incorporate canopy structure and if possible molecular considerations into its models. Fischer (2011) however, considers incorporating traits and their links to genes to be a challenging task that is yet to produce results that can be satisfactorily validated.

Statistical or time series models of environmental effects on yields can play an important part in wheat breeding. They are a means of quantifying the relationships between environment variables and their effects can be measured and crop yields compared between cropping areas (e.g. Carrathool and Wagga Wagga in this project), and possibly between years of high or low rainfall, or differing growing season rainfall and/or temperature distributions. The success of the time series model for yield predictions in this study (they were superior to the APSIM predictions) means they can be a useful tool for identifying the type of traits required for new varieties in a given area, both now and in coming decades, providing there is a reasonable historic yield and climate record available from that area to build the model. Analysis of the distribution of rainfall and heat during the growing season may also be useful. Chapman (2008) suggested that a substantial amount of genetic x environment variability can be due to the timing of drought stress. It may therefore be possible for a breeder to classify drought and/or heat stress patterns and then, using statistical analysis, identify wheat lines that have a broad or narrow adaptation to different rainfall or heat stress regimes.

6.2 **Conclusion**

The central theme of this research project was to identify the effects of above average growing season temperatures and heat episodes on rainfed wheat yields in Australia. As part of this investigation a series of research questions were raised and investigated:

6.2.1 **Is it possible to identify and quantify the relationship between rainfall and high temperature on wheat crop yields in southern NSW?**

The initial stage of the project established that there is a measurable effect and this could be best analysed by a) confining the investigation to a small portion of the Australian wheat cropping area and b) the use of statistical modelling to both separate and quantify the closely related effects of rainfall and heat on wheat yields. High degree hours (HDH) and growing season rainfall are closely correlated to each other (R=-0.63) and to yield (HDH R=-0.66, rainfall R=0.67). A combination of statistical modelling and 3D plots, of wheat yields against growing season rainfall and high degree hours (HDH), indicated a separable and measurable effect of HDH and rainfall on yields. The effects of HDH are most evident when growing season rainfall is in the 15-45% below average range. The relative effects of HDH and rainfall vary among districts. Rainfall is more critical in the warmer and drier areas whereas HDH has relatively greater influence in cooler wetter areas.

6.2.2 To what extent do episodes of above average temperatures limit wheat yields in southern NSW?

The time series models indicated that the warmest/driest area (Carrathool shire) suffered an average 15% yield loss per season due to HDH and across the study area there was an average 5.3% reduction in yield for each 1°C rise in average growing season temperature.

6.2.3 Are there major differences between the statistical (time series) and the APSIM model wheat yield predictions?

The APSIM simulation program has been used for yield prediction under varying climate scenarios, including higher temperatures (Asseng *et al.*, 2011; Power *et al.*, 2004; Wang *et al.*, 2011). A comparison of the APSIM yield predictions with those of the statistical model, using the same climate record and comparing with observed yields, indicated that yield predictions using the statistical model were superior. However, the main difference between the two sets of predictions was that APSIM attributed larger yield reductions to rainfall deficit than the statistical model, whereas the statistical model predicted greater yield reductions for increased average temperature. Based on these data and also from an analysis of the APSIM residuals (predicted versus observed) against HDH, it was concluded that APSIM did not accurately model the damaging effects of higher than optimal temperatures during wheat reproductive stages.

The sensitivity analysis compared the predictions of the statistical model against those of APSIM for a 1°C rise in average growing season temperature and/or a 10% reduction in growing season rainfall. The predictions were similar for the combined conditions. However, when the conditions were simulated individually, APSIM predicted higher yield losses than the statistical model for the decreased rainfall condition and the statistical model predicted higher losses than APSIM for the increased temperature condition. This may be due to deficiencies in the methods APSIM uses to model heat stress during the reproductive stage of the wheat crop.

6.2.4 Are selected overseas wheat research lines more heat tolerant than current Australian varieties?

The field and greenhouse experiments showed superior yields for some of the overseas germplasm compared with the selected local varieties, but the ranking of the varieties varied between testing environments and testing dates. There was a significant genotype x environment and genotype x date interaction. The degree and timing of heat stress is obviously an important consideration when deciding which genotypes are superior performers, whether based on field or greenhouse experiments. Each experiment is likely to have tested a different aspect of heat tolerance, i.e. the greenhouse experiment only tested heat tolerance at the pollination/fertilisation stage, whereas the field experiments were designed to test heat tolerance at all developmental stages.

6.2.5 **Final thoughts**

Given that wheat crops in many parts of Australia are already subject to significant heat stress, and this stress is predicted to increase, the field and greenhouse data are a useful contribution to a larger testing program of wheat research lines that will lead to the establishment of better performing wheat varieties for future Australian wheat farmers. The field experiments highlight the extent of the environment x genotype interactions and the necessity to target experiments such that they truly characterize the ability of new wheat varieties to withstand the timing, extent and concurrence of abiotic stresses, such as heat and drought. Additionally, the modelling experiments highlight that both the APSIM and statistical models are useful tools for the wheat breeder, especially when the aim is to quantify past effects of heat and rainfall on wheat yields and, given climate variability, predict future outcomes. With further modifications, such as improved heat stress simulation in APSIM and the inclusion of heat and rainfall distribution analysis in the statistical models, modelling can potentially contribute even more to the targeting and efficiency of future wheat pre-breeding and breeding programs.

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APPENDICES

APPENDIX A Literature Review

Table A-1. Reproductive stage heat stress experimental setups and measurements

Researcher	**(Wheeler *et al.*, 1996)**			
Crop	Winter wheat cv. Hereward			
Setup	Temp. Gradient tunnels, 275-300 plants/m2. Apply range of temperatures and CO2			
Temperatures:	Gradients applied as constant increment to ambient temperature			
Measurements:	(results for heat only)			
Grain number	Reduced by > 31C immediately before anthesis. Reduced from 35 per ear at 14-17ºC mean seasonal temperature, to only 5 at 22.5C mean seasonal temperature			
Seed yield	Reduced by higher mean seasonal temperature			
Biomass	Reduced by 10-24% for 1C increase in seasonal temperature			
Researcher	(Ferris *et al.*, 1998)			
Crop	Spring wheat			
Setup	Temp. Gradient tunnels, 376 plants/m2.			
Temperatures:	Gradients applied as constant increment to ambient temperature from 70 to 82 days after sowing (anthesis) Range from 2ºC to 9 ºC above ambient			
Measurements:				
Grain number	Declined with increasing max temp post anthesis, including 1 day post anthesis			
Grain yield	Declined sharply with max temp at 78 DAS (50% anthesis)			
Researcher	(Kaur and Behl, 2010)			
Crop	Wheat WH730 (high temp. Tolerant) and UP2565 (high temp. Sensitive)			
Setup	Poly bags, 6kg soil, 4 plants/bag, moved from screen house to polyhouse for heat			
Temperatures:	Ambient 10C-26C. One week of 5-8C > ambient at booting stage, at post anthesis, and at both stages			
Stage	***Duration***	***Day temperature ºC***	***Night temperature ºC***	***Transition rate***
booting	1 week	31 - 34	15 - 18	
Post-anthesis	1 week	31 - 34	15 - 18	
Booting and post-antheisis	1 week	31 - 34	15 - 18	
Measurements:				
Grain number	For HT, grain number Control > post-anthesis > boot > boot+post-anthesis. WH730 > UP2565			
Grain yield	For HT, grain yield Control > post-anthesis > boot > boot+post-anthesis. WH730 > UP2565			
Grain weight	For HT, grain weight: post-anthesis > Control > boot > boot+post-anthesis. WH730 > UP2565			
Researcher	(Ugarte *et al.*, 2007)			
Crop	Wheat, barley, triticale			
Setup	Irrigated, field, 350 plants/m2, heating used transparent chambers with electric heating			
Temperatures	1st 2 years: booting-anthesis and heading-anthesis 3rd year: stem elongation-booting and booting-anthesis Average 5.5C above ambient			
Measurements:	Results for wheat:			
Grain number	HT at stem elongation-to-booting reduced GN 41%, at booting-to-anthesis 9%, at heading-to-anthesis 8%			
Grain yield	HT at stem elongation-to-booting reduced yield 45%, at booting-to-anthesis 25%, at heading-to-anthesis 16%			
Grain weight	Decreased up to 13% when heated during booting-to-anthesis			
Researcher	(Prasad *et al.*, 2008)			
Crop	Wheat cultivars Seri-82, Pavon-76			
Setup	4 x growth chambers, 21cm pots, 3 plants/pot (= approx. 100/m2),			

Temperatures:							
Stage	***Duration days***	***Day temp. ºC***	***Duration hours***	***Night temp. ºC***	***Duration hours***	***Transition hours***	***Photoperiod hours***
Sowing to booting	continuous	24	10	14	10	2	
Booting to harvest	continuous	24	10	14	10	2	
Booting to harvest	continuous	24	10	17	10	2	
Booting to harvest	continuous	24	10	20	10	2	
Booting to harvest	continuous	24	10	23	10	2	
Measurements:							
Photosynthesis	Decreased as night temperature increased						
Seed set	Decreased as night temperature increased						
Grain fill duration	Decreased as night temperature increased						
Grain yield	Decreased as night temperature increased						
Researcher	(Wardlaw *et al.*, 1989b)						
Crop	Wheat – range of cultivars						
Setup	Glasshouse, 12.5 cm pots						
Temperatures:							
Stage	***Duration days***	***Day temp. ºC***	***Duration hours***	***Night temp. ºC***	***Duration hours***	***Transition hours***	***Photoperiod hours***
Sowing to booting	continuous	18	8	13	16		16
Booting to anthesis	continuous	24	8	19	16		16
Booting to anthesis	continuous	30	8	25	16		16
anthesis	5	24	8	19	16		16
anthesis	4	30	8	25	16		16
grain development	continuous	24	8	19	16		16
grain development	continuous	30	8	25	16		16
Measurements:							
Grain number	Reduced by high temp during booting						
Grain size	Reduced by high temp during grain development						
Grain weight	Reduced by high temp after anthesis – had largest effect on grain yield (Wardlaw *et al.*, 1989a)						
Researcher	(Wardlaw *et al.*, 1989a)						
Crop	Wheat 66 cultivars - to establish variability						
Setup	Glasshouse, 12.5 cm pots						
Temperatures:							
Stage	***Duration days***	***Day temp. ºC***	***Duration hours***	***Night temp. ºC***	***Duration hours***	***Transition hours***	***Photoperiod hours***
Sowing to booting	continuous	18	8	13	16		16
Anthesis + 6 days	continuous	35	8	20	16		16
Measurements:							
Grain weight	Reduced by high temp 30-35% for Australian cultivars						
Researcher	(Gibson and Paulsen, 1999)						
Crop	Winter wheat Karl 92						
Setup	Greenhouse, 36 plants per 61cm tub, 144 plants/m2,						
Temperatures:							
Stage	***Duration days***	***Day temp. ºC***	***Duration hours***	***Night temp. ºC***	***Duration hours***	***Transition hours***	***Photoperiod hours***
Sowing to anthesis+	continuous	30		20			
Anthesis + 10 days	continuous	25 30 35	8	20 20 20	8	4	16
Anthesis + 15 days	continuous	25	8	20	8	4	16

		30 35		20 20			
Anthesis + 20 days	continuous	25 30 35	8	20 20 20	8	4	16
Measurements:							
Grain number	Anth.+10 – decreased linearly, Anth.+15 – no effect, Anth.+20 – no effect						
Grain yield	Anth.+10 – decreased linearly, Anth.+15 – decreased linearly, Anth.+20 – no effect						
Researcher	(Saini and Aspinall, 1982)						
Crop	Wheat cv. Gabo						
Setup	Glasshouse, pots						
Temperatures:							
Stage	***Duration days***	***Day temp. ºC***	***Duration hours***	***Night temp. ºC***	***Duration hours***	***Transition hours***	***Photoperiod hours***
Sowing to meiosis	continuous	20		20			16
meiosis + 0, 3, 6 days	3	30		30			16
meiosis + 0, 1 days	1	30		30			16
meiosis+	3	30		20			16
Measurements:							
grains per spike	Greatest reduction when heat spike (3 days) in middle of meiosis (meiosis + 3 days)						
grain set	Greatest reduction when heat spike (3 days) in middle of meiosis (meiosis + 3 days)						
Researcher	(Shah and Paulsen, 2003)						
Crop	Wheat cv. Len						
Setup	Greenhouse, 21cm pots, 3 plants/pot Combination temperature and drought						
Temperatures:							
Stage	***Duration days***	***Day temp. ºC***	***Duration hours***	***Night temp. ºC***	***Duration hours***	***Transition hours***	***Photoperiod hours***
Sowing to anthesis	continuous	25	16	20	8		
Anthesis to maturity	continuous	15	16	10	8		
Anthesis to maturity	continuous	25	16	20	8		
Anthesis to maturity	continuous	35	16	30	8		
Measurements:							
Grain weight	Weight increased until anthesis + 3 weeks for 35/30, anth. + 4 weeks 25/20, anth. + 5 weeks 15/10						
Researcher	(Talukder *et al.*, 2010)						
Crop	Wheat genotypes (Excalibur, Krichauff, Gladius and Janz)						
Setup	Field, moveable transparent heat chambers						
Temperatures:							
Stage	***Duration days***	***Day temp. ºC***	***Duration hours***	***Night temp. ºC***	***Duration hours***	***Transition hours***	***Photoperiod hours***
Green anther	1	35	3			Stepped	
Anthesis + 7-10days	1	35	3				
Measurements:							
Grain yield	First and second treatments decreased grain yields by 18 and 19% in Excalibur, by 19 and 22% in Krichauff, by 21 and 26% in Gladius and by 35 and 30% in Janz						

APPENDIX B Literature Review

Table A-2. Weather data for selected wheat growing areas NSW and Southern Queensland (BOM, 2011).

Narrabri West Post Office 1962-2002	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
High Max (°C)	43.4	42.3	40.6	37.2	31.3	26.9	26.7	32.1	36.6	40.7	43	43.3
Mean Max (°C)	33.8	33.2	31.2	27.3	22.5	18.7	18	19.8	23.4	27.1	30.1	33
Mean Min (°C)	19.3	19.1	16.4	11.9	8.3	5.2	3.7	4.6	7.6	11.7	14.8	17.7
Av Days > 30°C	26.4	24	21.8	5.8	0.1	0	0	0.1	1.7	8	15.8	24.3
Av Days > 35ºC	13.1	9.2	3.6	0.1	0	0	0	0	0.1	0.9	4.1	11.3
High Min (°C)	28.3	27.4	24.7	21	19.8	15.2	16.4	17.6	21.1	24.7	26.9	28.3
Low Min (°C)	10.6	7.8	5.6	0.7	-2.2	-5.6	-4.4	-3.9	-1.7	-0.6	3.9	6.0
Gunnedah 1876-2011	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
High Max (°C)	48.7	44.4	45.0	37.2	34.4	30.4	26.7	31.1	35.4	40.0	43.3	46.1
High Min (°C)	34.4	30.0	25.6	23.9	19.1	18.9	14.4	15.8	20.0	23.9	29.4	28.9
Low Min (°C)	2.2	3.3	-1.0	-3.9	-5.3	-8.6	-8.3	-7.5	-6.7	-2.2	0.6	1.1
St George Qld. 1962-1997	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
High Max (°C)	45.0	43.0	40.5	37.2	32.6	26.8	28.8	34.4	36.2	40.7	43.3	44.0
High Min (°C)	29.6	29.7	26.8	22.8	19.8	16.5	16.2	24.2	22.0	25.8	29.7	30.0
Low Min (°C)	12.8	12.2	7.8	3.3	0.5	-2.2	-1.7	-1.0	1.5	4.9	8.3	11.1
Trangie 1968-2011	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
High Max (°C)	45	45.8	40.9	36	28.1	24.7	24	30.1	35.2	41.1	44.8	43.3
High Min (°C)	28.4	29.3	25.8	21	18.3	15	14	16.5	22	23.3	27.3	28.5
Low Min (°C)	8	7.2	4	-1	-1.7	-5	-5.4	-8	-3.5	0.1	1.6	6.2
Morawa Airport 1997-2011	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
High Max (°C)	47	47.2	43	37.9	35	28	26.7	32.4	36.2	39.6	43.7	46.8
High Min (°C)	30.4	29	28	22	23	15	15.1	17.1	24	25	29.3	30.4
Low Min (°C)	11	11.3	8.7	5	2.4	-1.9	-1.1	-0.2	0.8	2.5	4.4	7

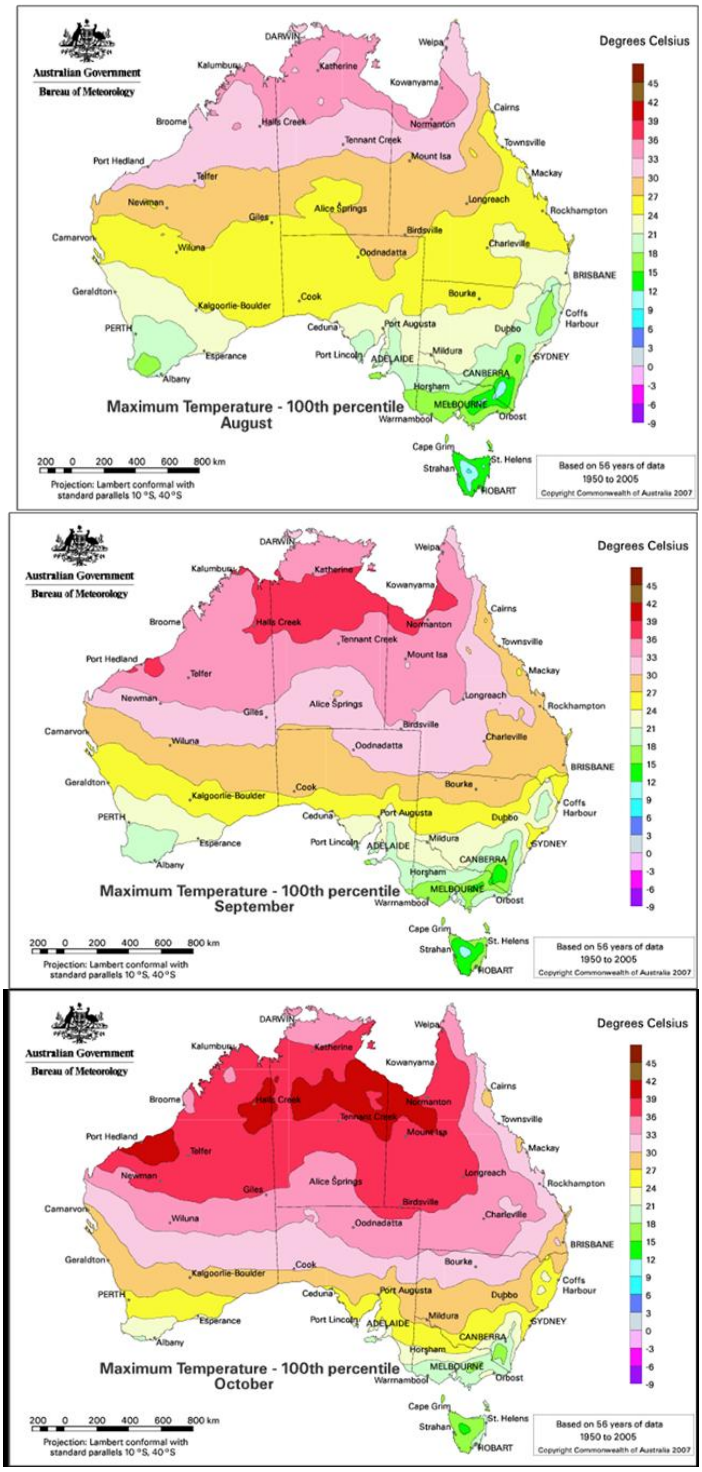


Figure A-1. Maximum temperature 100th percentiles for August – September in Australia (BOM, 2011).

APPENDIX C Time Series and APSIM modelling

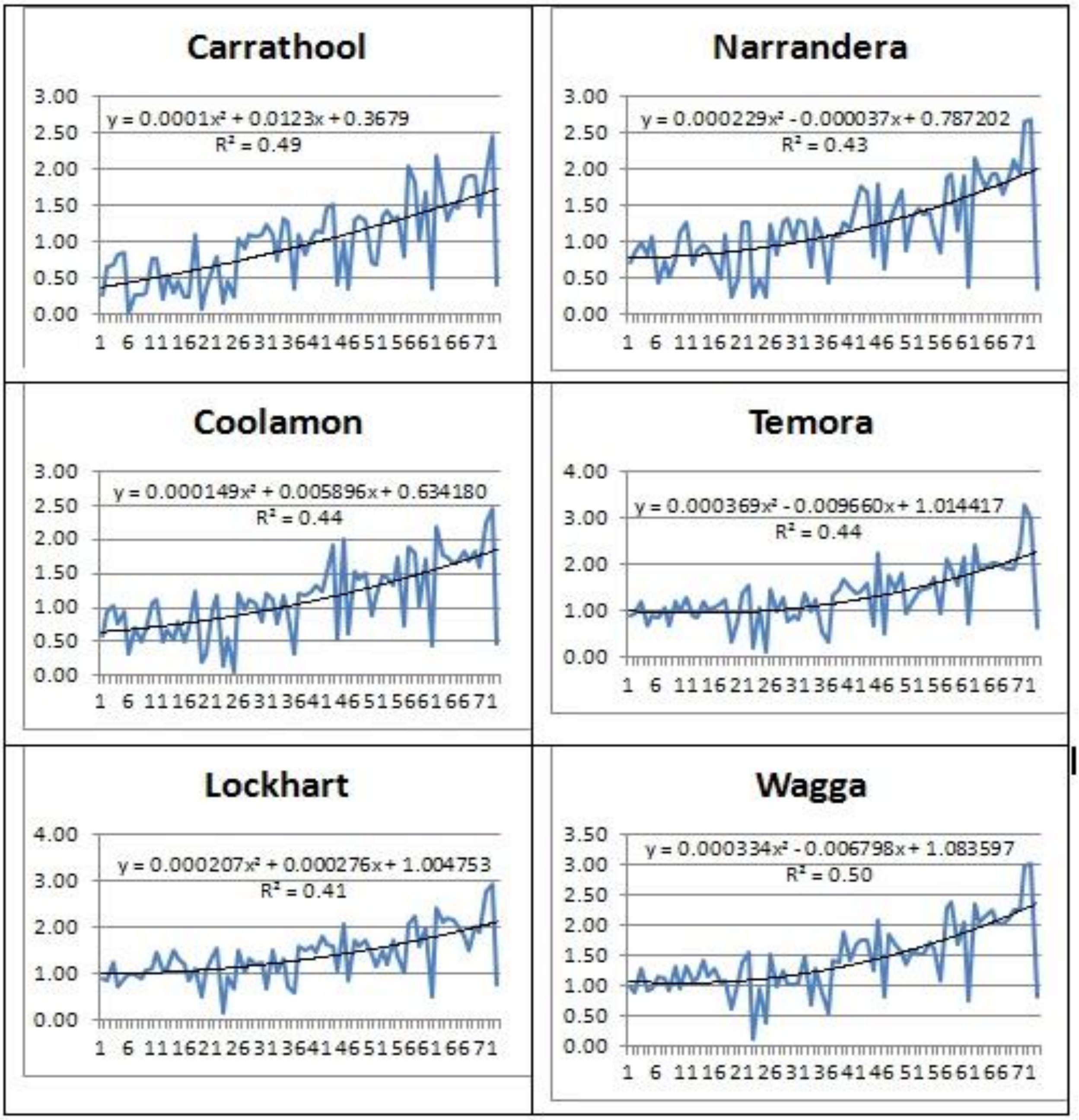


Figure A-2. Shires yields and fitted curves for de-trending wheat yield advances due to technology for years 1922-1994. Vertical axes are yields in t/ha and horizontal axes represent the 73 years time span.

Table A-3. NSW shires regression analysis statistics: Yield delta (as percent deviation from quadratic trend line 1922-1994) vs. rainfall (as percent of average growing season rainfall) and High Degree Hours (HDH), after removing seasons with greater than 30% of average rainfall from the analysis. - Simulation of wheat yields in southern NSW (using APSIM)

Carrathool: Observations=61, adjusted R=0.53						
	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	15.10	6.54	2.31	0.02	2.01	28.20
rf%	1.04	0.21	5.06	0.00	0.63	1.45
HDH	-0.09	0.04	-2.16	0.04	-0.17	-0.01

Narrandera: Observations=63, adjusted R=0.63						
	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	12.22	3.87	3.16	0.00	4.48	19.97
rf%	0.93	0.15	6.33	0.00	0.63	1.22
HDH	-0.09	0.04	-2.37	0.02	-0.16	-0.01

Coolamon: Observations=65, adjusted R=0.58						
	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	10.52	4.06	2.59	0.01	2.40	18.63
rf%	0.88	0.16	5.54	0.00	0.56	1.20
HDH	-0.16	0.06	-2.76	0.01	-0.28	-0.04

Wagga: Observations=63, adjusted R=0.44						
	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	9.85	3.37	2.92	0.00	3.11	16.59
rf%	0.57	0.15	3.90	0.00	0.28	0.87
HDH	-0.16	0.07	-2.33	0.02	-0.30	-0.02

Lockhart: Observations=61, adjusted R=0.43						
	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	14.13	3.59	3.94	0.00	6.95	21.31
rf%	0.57	0.15	3.76	0.00	0.27	0.88
HDH	-0.18	0.07	-2.62	0.01	-0.31	-0.04

Temora: Observations=60, adjusted R=0.46						
	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	12.46	4.21	2.96	0.00	4.03	20.88
rf%	0.73	0.16	4.49	0.00	0.40	1.05
HDH	-0.13	0.07	-1.90	0.06	-0.27	0.01

Combined SD150 Observations=63, adjusted R=0.63						
	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	10.51	3.38	3.10	0.00	3.74	17.28
rf%	0.84	0.14	6.05	0.00	0.56	1.12
HDH	-0.13	0.05	-2.66	0.01	-0.22	-0.03

Maximum temperatures and rainfall

The growing season rainfall (mm) for each the six shires (Carrathool, Narrandera, Coolamon, Temora, Lockhart and Wagga Wagga) within SD150 plotted against the average the growing season average temperature for each of those shires, illustrated the negative linear relationship between the two.

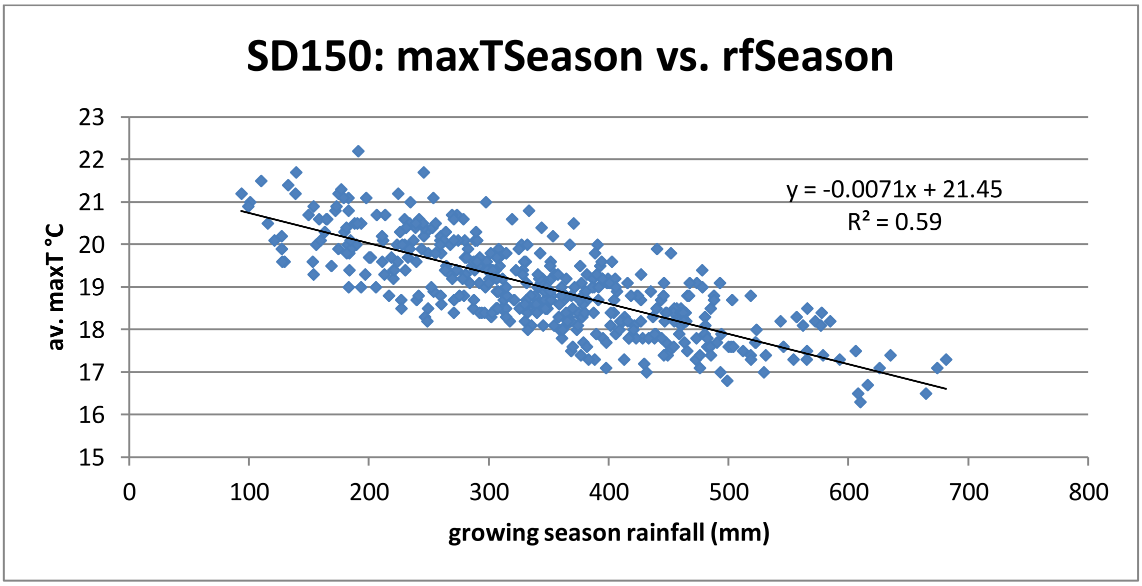


Figure A-3. Growing season rainfall compared with growing season average maximum temperate for the six selected shires in Statistical Division 150 (SD150) wheat cropping area 1922-1994.

Yield and rainfall

As rainfall increases beyond approximately 30% above season average, yields flatten and then decrease.

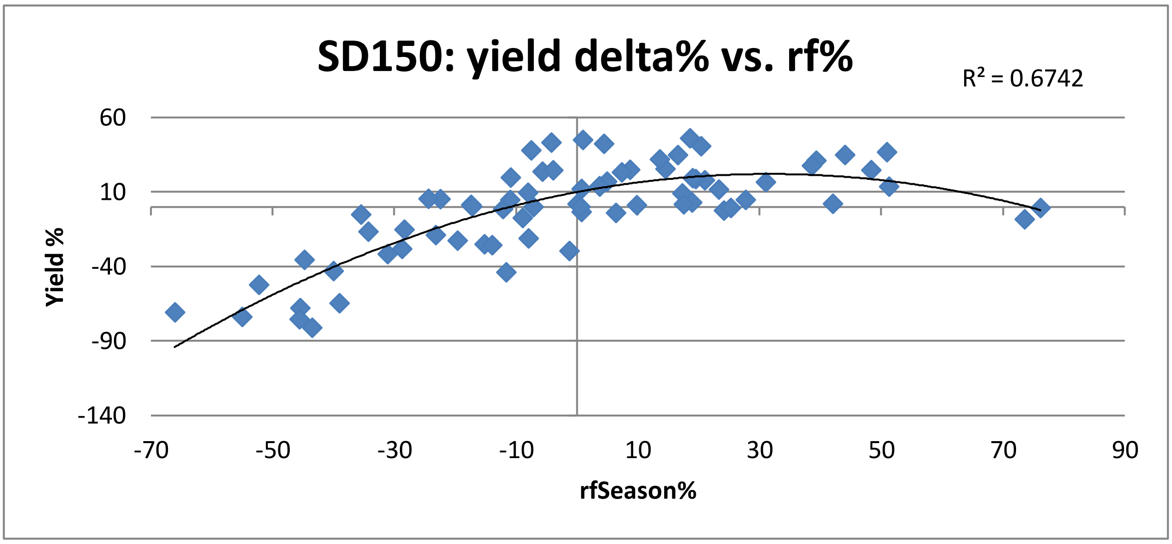
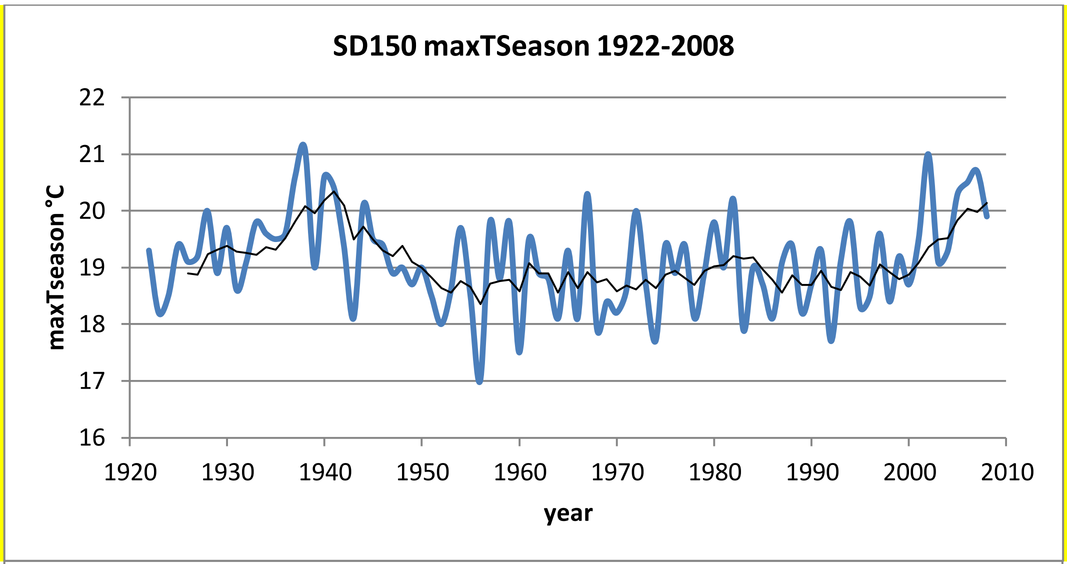


Figure A-4. Yield deviations (%) compared with growing season rainfall deviations (%) for six shires in Statistical Division 150 (SD150) years 1922-1994.

For both rainfall and temperature variables there were some minor trends over the study period. There was a period of higher temperatures in SD150 from 1935-1945. In SD150 temperatures also trend up from 1994-2008 and rainfall down over approximately the same period. The 1935-1945 high temperature episodes are comparable to the later 1994-2008 upward trend, so a model built using 1922-1994 weather variables should be calibrated to some extent for the range of temperature excursions that occur during the period 1994-2008. Similarly the range of rainfall deficits from 1935-1945 are comparable to those experienced from 1994-2008.



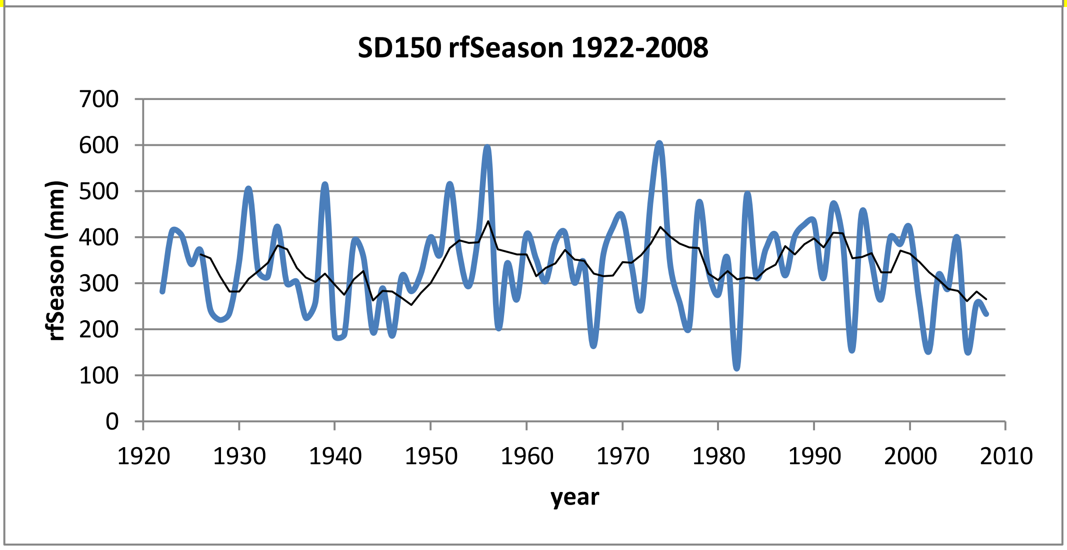


Figure A-5. Growing season maximum temperature (top) and growing season rainfall (bottom) trends for Statistical Division 150 years 1922-2008, the blue lines are the annual fluctuations, the dark lines are the 5 year moving averages.