Adapting Australian farming systems to climate change: a participatory approach

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Landcare & Catchment Management Queensland
Brigalow Jimbour Floodplains Group Inc.

Mingenew-Irwin Group

PROJECT DETAILS

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1. PROJECT OBJECTIVES

The overall objective of this research project was to explore options to increase the resilience of a range of broadacre farming systems across Australia to climate change by identifying vulnerabilities and subsequently exploring feasible adaptation options. This includes:

- taking a case-study approach, based on real farming systems and their management in three key (climatically and agronomically different) regions: the north-east, the south-east and the west.
- bringing the experience and knowledge of farmers in those regions into an evaluation of practical and useful adaptations to prospective climate changes.
- quantifying the benefits of those adaptation options in terms of agricultural productivity, economic returns and sustainability (see separate RM Consulting Group report)

2. FINAL REPORT REQUIREMENTS

The final report contains:

- an examination of regional climate trends in each of the three case study regions;
- a discussion of the potential adaptations options identified by farmers in the three case study regions in response to projected future climate trends;
- an assessment of both the economic and environmental benefits of those practical adaptation options at the farm level; and
- an examination of the regional implications of these adaptation options.

3. FINAL REPORT ACHIEVEMENT CRITERIA

Achievement criteria include:

- submission and acceptance of the report by The Department of Climate Change.

EXECUTIVE SUMMARY

This report documents an extensive quantitative assessment of the benefits of specific adaptation options to climate change. This was done via comprehensive engagement with farmers, producer groups and Catchment Management Authorities (CMAs) across three broad grain growing regions to identify practical management responses to climate change options and assess the value, in terms of productivity response, in a crop modelling framework. This research has extended the application of climate change information to assess potential crop production risk in several ways:

- For the first time, farmer defined adaptation options have been evaluated for three disparate grains regions in Australia to formally evaluate their regional effectiveness;
- For the first time, the impact of a range of possible future climate conditions have been examined across twelve case study farms to more rigorously compare the likely impacts of climate change on crop production. This has been achieved by modelling crop production at each site using climate information from two different climate models (HADCM3.1 and MARK3) each driven by a modest (A2 SRES emission scenario) and more extensive (A1T SRES emission scenario) global warming scenario;
- For the first time, detailed descriptions of twelve actual farms (crop production, existing crop and nutrient management, climate risk management, input and production costs) across three major farming regions have been collected through “participatory action research”, allowing an effective (and complex) risk management ‘baseline’ to be established against which the benefits of climate change adaptation can be more realistically evaluated. This approach has avoided the establishment of an artificially low baseline arising from the simplified, stylised representations used in many previous analyses;
- We have examined how adaptive farm management can offset or improve crop yields for all three regions and formally examined the cost/benefits implications of selected adaptation options for one site in each region;
- Generally, production in individual paddocks is assisted by improved water use efficiency measures such as fallowing, pasturing and enhanced residue management, however these may have negative implications for overall farm productivity;
- The method developed in this project to remove the rainfall ‘noise’ from the temperature ‘signal’ allows clear identification of significant climate trends in all regions with these trends differing between regions for some variables**.** These analyses raise significant questions about some commonly held assumptions about ongoing climate changes, identifying future research needs;
- Formal evaluation by the participants showed that this project increased their capacity to understand the value of climate information and provided additional insights regarding the likely impact of climate change on crop production, and potential ways to offset negative effects.

During the course of this project the research team has worked extensively with individual farmers, farmer groups and catchment authority staff in three major grains regions, namely southeast Queensland (Jandowae), northern Victoria (Birchip) and northern grain region of Western Australia (Mingenew) to identify a range of opportunities to adapt current management practices in response to projected climate change. Management adaptations included changes in crop rotations, crop density, crop variety, stubble and fallows or pasture management which were assessed singly

against a historical baseline for each farm from 1957 to 2006 and against a future 50 year baseline where no change in current management occurred. (Figure 1).

Twelve different farms were examined across the three grain growing regions using the Agricultural Production Systems Simulator (APSIM, Keating *et al*, 2003) parameterised individual soil parameters, rotations and management practices for each farm (Figure 1). The information presented in this final report represents an assessment of farm results across each of the three case study regions.

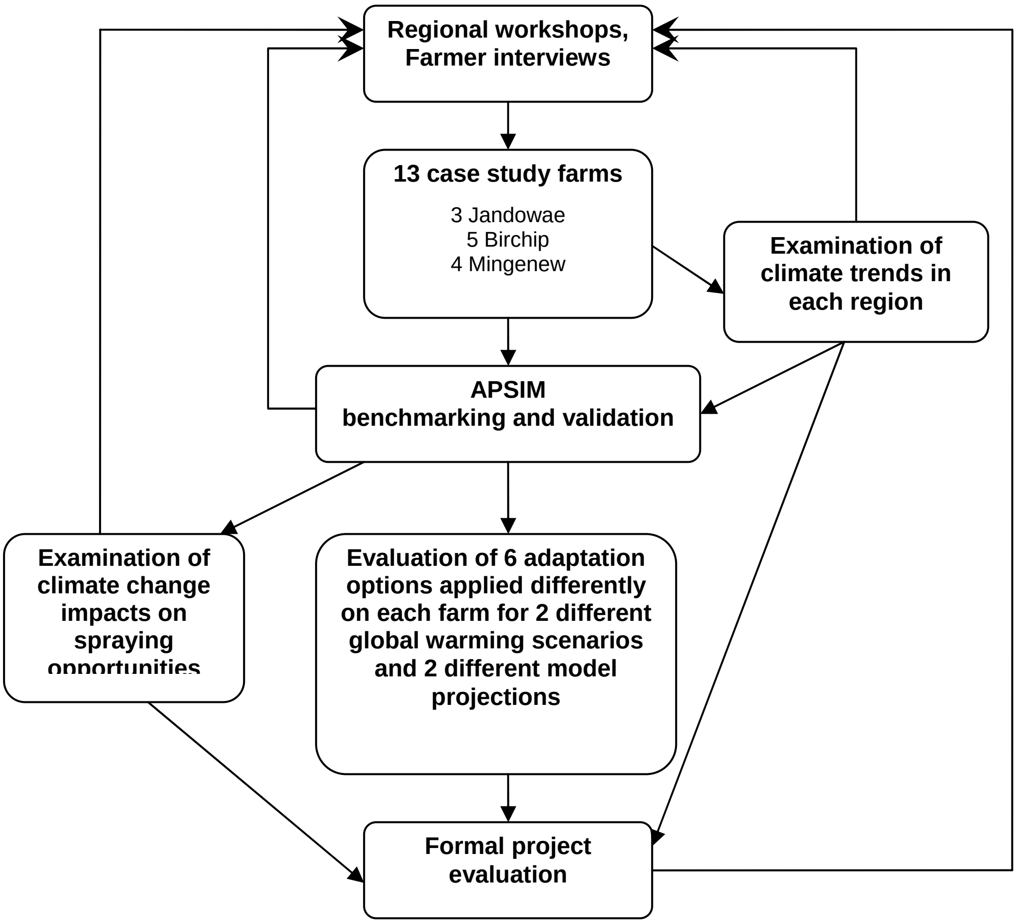

Figure 1: *Schematic representation of the research undertaken as part of this project.*

The analyses reported here indicate significant and sustained change in climate for all regions. In many cases (e.g. temperature increases around Jandowae) past changes are consistent with projections from the two climate models analysed. All three of the case study regions have experienced increases in average temperatures, and the Jandowae and Mingenew regions experiencing statistically significant declines in annual rainfall.

In some cases (e.g. minimum temperatures in the southern sites) trends are unexpectedly downwards: in which case there are inconsistencies with expectations of future changes. In the Birchip region the decline in annual minimum temperature (-0.02^{o}C/decade) combined with a strong trend of increase in the date of the last frost (4.9days/decade) have resulted in considerable increase in the exposure to frost risk. This is not the case with the Jandowae region, where annual minimum temperatures have increased by 0.18°C/decade and a significant reduction in the number of frosts per year (-1.9 frosts/decade) have occurred. Consequently, in these regions simple extrapolations of past change may be an inappropriate basis for exploring future management adaptations.

There is growing concern that changes in the climate system will have detrimental impacts on some agricultural systems. Agricultural systems may be negatively impacted due to changes in water availability, as well as heat stress and pest, disease or weed pressures (e.g. IPCC 2007b). For this reason, a strong incentive exists to enhance the adaptive capacity of agricultural systems in order to deal with further changes expected as a result of human-induced climate change.

Recent research on adaptation has followed a variety of paths; with the main focus on the evaluation of the benefits from general adaptation options. This past research has identified in broad terms the following adaptation options for cropping systems:

- "Altering inputs such as varieties/species to those with more appropriate thermal time and vernalisation requirements and/or with increased resistance to heat shock and drought, altering fertilizer rates to maintain grain or fruit quality consistent with the prevailing climate, altering amounts and timing of irrigation and other water management.
- Wider use of technologies to ''harvest'' water, conserve soil moisture (e.g., crop residue retention), and use and transport water more effectively where rainfall decreases.
- Managing water to prevent water logging, erosion, and nutrient leaching where rainfall increases.
- Altering the timing or location of cropping activities.
- Diversifying income through altering integration with other farming activities such as livestock raising.
- Improving the effectiveness of pest, disease, and weed management practices through wider use of integrated pest and pathogen management, development, and use of varieties and species resistant to pests and diseases and maintaining or improving quarantine capabilities and monitoring programs.
- Using climate forecasting to reduce production risk" (Howden et al., 2007, p19693).

Rather than simply identifying all possible adaptations for managing climate related risks, this current research project has sought to evaluate the suitability of adaptations according to criteria such as production impacts. This research project has examined these broad scale adaptation options and through engagement with production groups and individual farmers has evaluated adaptation options that, while achieving similar broad goals, are tailored to individual farming systems. Farmers were asked to identify a range of adaptation options they would consider implementing in order to reduce possible negative impacts on crop yields and hence farm production. A range of both tactical and strategic responses were identified (Table 1) and a subset of four tactical adaptation options were assessed at each site. These included:

- increasing fallow or pasture;
- reducing planting density;
- changing crop rotations (limited cases);
- selecting shorter season crops; and
- increasing residue retention.

The results from this study suggest that some adaptation options provide resilience to both modest and more extensive climate change across much of Australia. These adaptation options include the implementation of additional ‘fallow’ or ‘pasture’ components in the rotation and the enhancement of current residue retention practices. The additional ‘fallow’ or ‘pasture’ adaptation served to improve median yield production by between 4 to 55% for a modest global warming scenario, depending on region and positioning of the fallow in the rotation. The greatest improvements in median yield were returned in the Jandowae region (i.e. up to 55%) as the soils in this region have greater water holding capacity than the other two regions and thus benefit more from improvements in water management.

Improving crop and farm system water use efficiency (WUE) has been an important consideration of Australian farmers over the past 30 years. Many improvements in WUE have been attained through changed dryland farming practices such as minimum disturbance planting, varietal changes, better managed phase changes (pasture to crop and back) and summer fallow management (stubble and weeds). These adaptation options have had varying degrees of success in Australia depending on regional constraints. Outcomes from this project would suggest that this will be a continued challenge in the future. These constraints include:

- “Physical - soil types, depths, and characteristics, field layout, water sources and sinks, water distribution systems, farm technology and machinery.
- Climatic - heat and other extremes, drought potential, rainfall amounts and intensities, vapour pressure deficit and sunshine.
- Economic - material availability, labour cost and availability, and investment capacity.
- Social - governmental regulations/incentives, environmental concerns, safety considerations” (Izuno, 2002).
- Information – information gaps, communication issues

Some adaptation options proved of little production value across all three case study regions. These included reducing planting density and changing crop variety. In the case of changing crop density, this adaptation resulted in lower median yields under both modest and extensive climate change conditions compared with yields resulting from no change in current management. These differences were larger in the Jandowae region (i.e. between 2 to 8% lower median yields than the ‘no change’ case) than in the Birchip region (i.e. less than 1% to 4% lower median yields than the ‘no change’ case). In the Mingenew region this adaptation option had mixed results providing yield benefits over the ‘no change’ case.

Changing to shorter season varieties proved an inadequate adaptation option in both the Jandowae and Birchip regions; resulting in lower simulated yields compared against yields resulting from no change in current management in most cases. In the Mingenew region this adaptation option proved more valuable, resulting in higher median yields in comparison with no change in current management. These results should be evaluated with some caution, as the choice of shorter season variety was dictated by the individual farmer response. The results may reflect a less appropriate choice of varieties in both the Birchip and Jandowae regions, and thus selection of different crop varieties should not be discounted based on the results from this study. A more appropriate way of variety selection should involve both farmer expert knowledge and modelling studies to optimise varietal selection.

Changed crop rotation was examined on two farms: one in the Birchip region and one in the Mingenew region. Results from this adaptation option were mixed. In the Birchip region changing the rotation to remove fababeans and include fallows before canola and wheat served to improve the yields in the lowest 25% of years, but also reduced yields in the uppermost 25% of years. For these reasons the adaptation option was successful at reducing the variability of wheat yields but resulted in lower median yield over all (i.e. 4% lower than the baseline yield of 3730kg\ha). In the Mingenew region the changed rotation included shortening a 13 year rotation to a seven year rotation, by reducing the number of lupin and oat crops. This adaptation option had the same effect as in the Birchip region (i.e. improving lowest 25% of yields and reducing upper 25 of yields), however the impact on the upper 25% of simulated yields was not as significant, thus resulting in a 2 to 5% improvement in median yields compared to the 1957 to 2006 baseline.

While yield is an important indicator of the effectiveness of a particular adaptation option the evaluation process must include a consideration of the economic and social implications as well. Adaptations which improve the prospects for wheat productivity may have negative effects on other crops in the rotation, or on the overall financial returns over a period of time.

Within the scope of this research project, two approaches have been taken to gain an insight into the potential economic implications of implementing the adaptation options identified by individual farmers. These were:

1. simple gross margin analyses have been conducted on the entire crop rotation, for the APSIM focus paddock only, for one farm in each of the case study regions, for the more extensive global warming scenario; and
2. more extensive whole-of-farm analyses for farms in the Birchip region, undertaken by RM Consulting Group, taking into account detailed farm economics, commodity and cost prices, and opportunity costs mentioned above (e.g. fallows) – contained in a companion report.

The simple gross margin analysis highlights that adding an extra fallow or pasture component in a rotation, while improving wheat yields, comes at an economic cost in terms of loss of income during fallow and, to a lesser degree, paddock phases, and loss of productivity for other crops in the rotation. Enhancing residue retention appears to have both positive productivity implications as well as economic impacts across all three regions.

This would suggest that the most successful national adaptation options, namely enhanced fallow/pasture and residue retention must be used in a more opportunitistic way in combination with improved seasonal climate forecast information so as to maximise implementation during dry years and minimise implementation during wet years

In addition to evaluating tactical adaptation options identified by farmers, we also considered examining the impacts of changing temperature and relative humidity on spraying opportunities (i.e. herbicide, pesticide, fungicide spraying). The analysis undertaken in each of the three regions examined current optimal times for herbicide spraying (as a function of appropriate temperature and relative humidity conditions) as well as the impact that climate change may have on these optimal spraying windows.

The frequency of climatic conditions unsuitable for spraying agri-chemicals appears to be likely to increase due to climate change. This increase could be around 30% by 2030 if both Delta T changes and potential changes wind speed are considered. In this study we have shown an increase unsuitable spraying conditions of up to 13% considering potential changes in Delta T. This may pose further challenges to farmers in their struggle to effectively control summer weeds. If weeds cannot be effectively controlled, less soil moisture will be available for planting winter crops. This could lead to farmers being forced to take increased risks through sowing their winter crops into a dry profile.

The conclusions of this research are that the effectiveness of any adaptation option will depend on the complex interaction of soil types, field layout, farm technology and machinery, the extent of future projected climate change, labour cost and availability, and investment capacity and external markets, to name but a few. The research from this project has shown that across these three disparate regions and different farming systems, attempts to conserve moisture in the soil through fallowing, increasing pasture in the rotation and residue retention all serve to offset potential yield losses through changes in temperature and rainfall. However, given the almost unique conditions (i.e. physical, social and economic) on each farm it is an extremely challenging task to identify adaptation options which will suit all farms across the nation, or even groups of farms within a region. The future of climate change adaptation research in this area will require strong participatory engagement processes to ensure that science (i.e. climate or crop) is effectively integrated with individual farmer management capabilities.

This project has attempted to examine the effectiveness of a range of adaptation options in the context of only a few of these drivers, but acknowledges that actual farm level decisions are seldom made with respect to just one stimulus. Hence, what may appear to be the most appropriate technical response at the farm level, given the risks associated with climate change, may not be the response which the farmer undertakes, due to associated reasons (social, financial).

The research reported here shows that there is considerable value in combining expert farmer knowledge with existing biophysical and economic models in a way that captures greater consideration of all preconditions (i.e. physical, economic and social) at each farm. Some efforts have been made to develop these more integrated approaches (e.g. Kokic *et al*., 2006), however further work is required to streamline these approaches to ensure they can effectively evaluate a range of adaptation options.

A formal evaluation of this research project was undertaken with participating farmers. The results clearly indicated that the project has increased their knowledge regarding the value of considering both climate change and seasonal climate information. Many (63%) said it had increased their capacity to respond to climate change information, encouraging them to use this information in a pro-active way.

All of the evaluation respondents indicated that the project had increased their understanding of climate risk management for production with the majority (88%) indicating that significant additional insights had been gained particularly with respect to fallow through the demonstrated benefits of sub-soil moisture on yields.

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INTRODUCTION

There is now strong evidence that human activities are serving to increase the global concentrations of atmospheric greenhouse gases (GHG) (IPCC 2007a). As a result of GHG increases, warming of the earth's climate system has been observed, as evidenced by increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level (IPCC 2007a). Continued greenhouse gas emissions will result in further warming and induce additional changes in the global climate system (IPCC 2007a). There is a growing concern that these additional changes will have detrimental impacts (e.g. yield, quality) on many cropping systems through changes in water availability, heat stress and pest, disease or weed pressures (IPCC 2007b).

It is well understood that Australian agricultural systems and the industries that support them are highly dynamic and sensitive to fluctuations in both climate variability and climate change (Carberry *et al.,* 2000; Hammer et. al., 1996; Hammer 2000; Howden *et al.,* 1999, 2001, 2003; Meinke and Hochman 2000; Meinke *et al.,* 2003). The ability of agricultural systems to adapt to both these elements of climate risk has been recognised as a key driver in production success or failure.

A great deal of information now exists regarding the nature and extent to which regional changes in temperature and rainfall have already occurred in Australia (Alexander 2007; CSIRO 2007; Nicholls 2007; Nicholls and Collins 2006) as well as how these changes will continue in the future (CSIRO 2007; IPCC 2007a). Far less information is available regarding the likely impacts of climate change on Australia's agricultural industries (IPCC, 2007b) and subsequently what effective adaptation options may be available in the future.

As part of this research project we have acknowledged this diminishing hierarchy of information and attempted to develop an investigative framework that combines climate science, expert farmer knowledge and crop modelling capability to evaluate a range of adaptation options across three disparate agricultural regions in Australia.

In order for adaptations to climate change to be successful they will need to be integrated effectively within the broader agricultural decision making and management context that already accounts for a range of existing pressures resulting from social, economic and institutional change. For this reason the introduction of new adaptation measures will not only have to reflect these existing pressures but serve to enhance current 'best-practices' to deal with climate extremes. This will only occur if there is:

1. "confidence that climate changes several years or decades into the future can be effectively predicted against a naturally high year-to-year variability in rainfall that characterises these systems;
2. motivation to change to avoid risks, or make use of opportunities;
3. development of new technologies and their benefits demonstrated;
4. protection against establishment failure of new practices during less favourable climate periods;
5. alteration of transport and market infrastructure to support altered production; and
6. continuing adjustments and improvements in adaptation by 'learning by doing' via targeted monitoring of adaptations to climate change and their

> costs, benefits and effects as our understanding of climate changes and adaptations improves" (McKeon et al. 1993; Howden et al., 2007).

Adaptation strategies that incorporate the above considerations are more likely to be of value, as they will be more readily incorporated into existing on-farm management strategies.

In this Final Report, we outline the approach taken to identify and evaluate the effectiveness of adaptation options in three disparate agricultural regions in Australia. We include a description of the regional climate trend information, the results of participatory engagement with producers, and the evaluation of adaptation options using the APSIM cropping systems model (Keating *et al.,* 2003). APSIM was used to simulate annual crop rotations with and without the adaptive management strategies suggested by farmers. A comparative analysis of these simulations provides important insights into which adaptations options provided benefits across all three regions, which provided only regional or farm specific benefits, and which provided no benefits at all.

Background

Australia has a variable and changing climate

Australia's agricultural industries are heavily impacted by both climate variability and change (Carberry *et al*., 2000; Hammer *et al*., 1996; Hammer 2000; Howden *et al*., 1999, 2001; Meinke and Hochman 2000; Meinke *et al*., 2003). The variable nature of Australian rainfall has had a strong role to play in the location and success of many agricultural enterprises. Traditionally, winter and summer crops have been grown in regions receiving between 320 and 700 mm of annual rainfall and experiencing "low" to "moderate" inter- and intra-seasonal rainfall variability (i.e. where variability is measured as the 90th percentile annual rainfall minus the 10th percentile annual rainfall divided by the 50th percentile rainfall) (Figure 2).

The ability of agricultural systems to adapt to climatic variability has been recognised as a key driver in production success, with failure to adapt responsible for excessive production variability and related resource degradation. To remain economically and environmentally sustainable under such variable climate conditions requires a sound understanding of the drivers of climate variability and the extent to which these can be predicted. This knowledge then needs to be translated into practical risk management strategies for avoiding economic and environmental losses in poor seasons, and to take advantage of favourable seasons (Meinke *et al.,* 2001, Meinke and Stone, 2005).

It has also long been recognised that long-term climate change will be experienced by farmers through changes in intra- and inter-seasonal variability and extreme events (Yohe, 2000; Smit and Pilifosova, 2001; Meinke *et al*., 2001, 2003). Farmers who improve their capacity to manage climatic variability and extreme events will be better placed to deal with the challenges of human induced climate change (Meinke *et al*., 2001, 2003; Bradshaw *et al*., 2004; Meinke and Stone 2005).

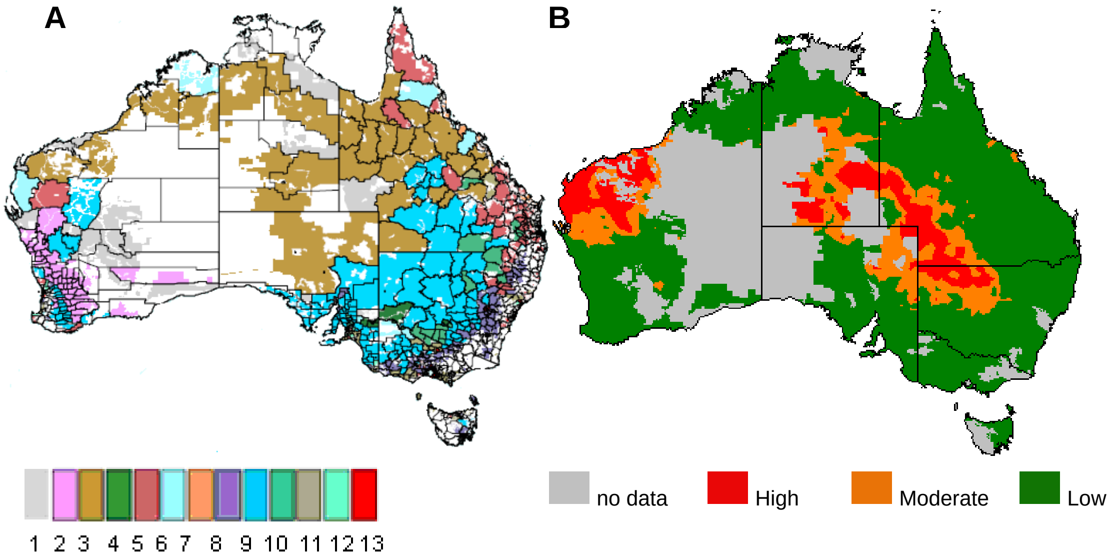


Figure 2: *a) Location of farming activities in Australia. The landuse activities are classified as follows: 1. Unclassified, 2. West Australian cropping, 3. Central Rangelands, 4. Horticulture, 5. Low Income Beef, 6. Fruit and Broad acre Country, 7. Cane, 8. Hill Country, 9. Mixed Farming Heartland, 10. Closer Settled Cropping, 11. Closer Settled Grazing, 12. Less Intensive Peri-urban, 13. More Intensive Peri-urban (Source: LWA 2005). One dot represents 2,500 hectares of crop sown. b) A map of annual rainfall variability for Australia. Rainfall variability was calculated using the coefficient of variation measure (the ratio of the standard deviation to the mean).*

Actions to offset the risks associated with both climate variability and change have been collectively defined as '*adaptation*'. In broad terms adaptation includes responses by individuals, groups and governments that serve to reduce their vulnerability or susceptibility to adverse impacts or damage potential (Holling, 1973, Bradshaw *et al*., 2004). "Adaptation comes in many forms and can be characterised according to a suite of attributes such as intent (spontaneous versus planned), timing (reactive, concurrent or anticipatory), duration (short- versus long-term), spatial extent (localized or widespread) or responsibility (e.g. government, producers, etc.)" (Bradshaw *et al*., 2004: 122).

In agriculture, adaptation to climate change includes tactical changes to management such as changing the timing of planting or varying the inputs such as fertiliser, sowing rate, row spacing etc. Adaptation options can also be strategic and include actions such as altering soil management practices such as tillage or selection of different crop types, varieties or rotations and by diversifying the farm enterprise mix or off-farm income stream (Hammer *et al*., 2001; Meinke *et al*., 2001; Bindi and Howden, 2004, Bradshaw *et al*., 2004).

A participatory approach to identifying adaptation options

During the course of this project the research team has worked extensively with individual farmers, farmer groups and catchment authority staff in three grains regions, namely southeast Queensland (Jandowae), northern Victoria (Birchip) and northeast Western Australia (Mingenew) to identify practical adaptation options to climate change. The regional locations of case-study farms are shown in Figure 3. A series of regional workshops were undertaken to present local climate trend and projection information to farmers and farmer groups. Workshop participants were asked to identify on-farm management adaptation options they would consider implementing to offset likely impacts associated with the climate projection information presented. There was significant commonality between the three regions in regard to the adaptation options identified and included changes in planting dates, crop rotations, crop density, crop variety, fertilisation and stubble management . A synthesis of common adaptation options is presented in Table 1.

***Table 1**: Adaptation options identified by farmers in response to their perceived risk of climate change across all regions.*

Tactical responses to climate change	**Strategic responses to climate change**
• Reduce the proportion of higher risk crops grown e.g. legumes	• Increase the size of the property including sandier soils.
• Reduce the amount of canola grown, although be prepared to be more opportunistic.	• Begin considering buying land in other areas that are more suited to cropping in the future.
• Fallow on a regular basis on heavier soils (crop less). Crop a greater proportion of the lighter soils on a more regular basis to compensate for smaller rainfall events.	• Begin to alter the cropping and livestock mix on the farm. (Note: some farmers indicated increasing the mix of cropping and livestock whereas others suggested moving from cropping to a more livestock orientated enterprise)
• Select for shorter season varieties and more heat tolerant crops in springtime.	• Move towards lower input farming, lower risk farming methods. This may result in lower year-to-year gross profit but longer-term profitability may be higher as conditions become drier and warmer.
• Lower stocking rates and retain more stubble to conserve soil moisture.	• Sell out or retire.
• Increase the diversity of crops grown on the farm.	• Buy light soil types
• Only grow legumes and canola on soils that have been long fallowed.	• Diversify into more off farm income sources e.g. feed lots for sheep/cattle
• Increase the length of fallow and proportion of the property fallowed.	• Look more into zero till by retaining all stubble and even look at biological farming practices.
• Sow a larger percentage of the crop on paddocks that have been long fallowed.	• Increase involvement in field trials that examine the use of varieties better suited to future climate conditions.
• Consider growing more fodder crops and move out of wheat cropping.	• Improve marketing to increase cash returns, consider less weather dependent business investments.
• Reduce the level of cultivation in order to minimise soil disturbance e.g. greater use of minimum till.	
• Increase row spacing and density of plantings.	

Individual interviews were also undertaken in each of the three study regions in order to gather information required to model individual farming systems and test a subset of adaptation options. Three farming systems were examined in the Jandowae region, five in the Birchip region and four in the Mingenew region. Details regarding each farming system are contained in the "**Data and Methods**" section below.

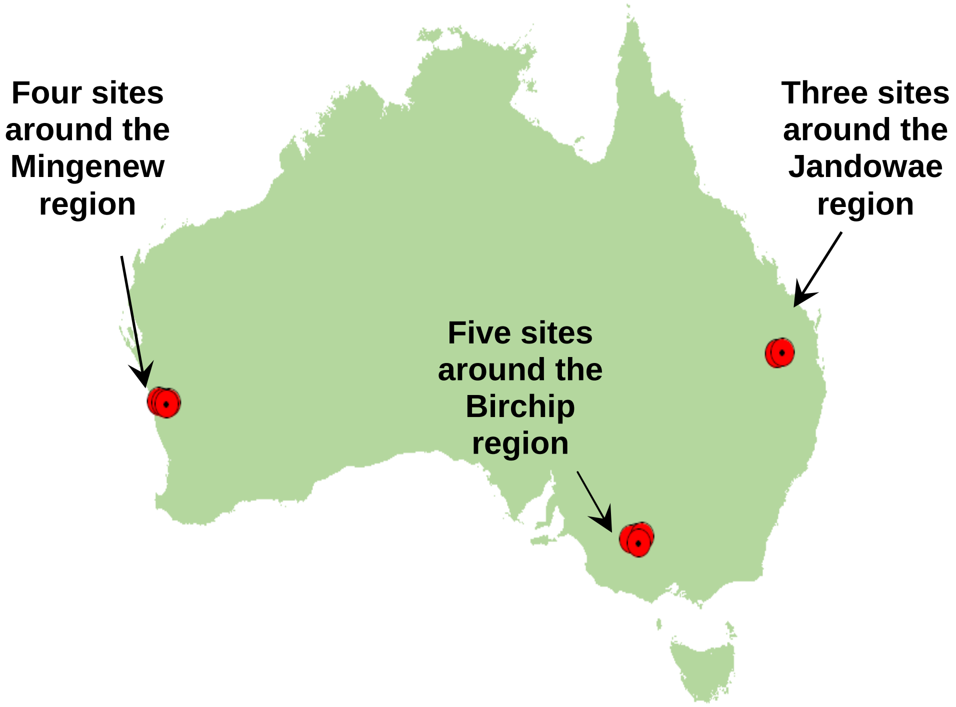


***Figure 3**: Location of case study regions and individual farms in the Jandowae, Birchip and Mingenew regions.*

Evaluating adaptation options to climate change using agro-ecological models

Changes in rainfall and temperature are not the only determinants of yield and factors such as starting soil moisture, planting dates and timeliness of rainfall strongly influence final yields. Simulation models integrate all these effects in a physiologically meaningful way.

The APSIM framework was chosen to examine the adaptation options to climate change nominated by farmers as it has been used in a number of similar climate variability applications (Angus *et al.*, 2001; Asseng *et al.*, 2001a,b; Carberry *et al.*, 2000; Hammer 2000; Hammer *et al.*, 1996; Meinke and Hochman, 2000; Meinke *et al.*, 2001, 2003) and has a proven track record in successfully integrating not only climate and management interactions but a range of other determinants that may have secondary impacts on productivity and resource condition e.g. soil processes, crop processes. APSIM is not limited to wheat cropping but is constructed around an array of different modules. These modules include a diverse range of crops, pastures and trees, and a full range of management controls allowing not only variations in productivity to be assessed but also resource condition indicated by outputs such as run-off, deep drainage and nitrogen leaching/leakage (Keating *et al.*, 2003).

DATA AND METHODS

Observed climate information

Climate data used in this study were obtained from the Queensland Climate Change Centre of Excellence SILO climate database (Jeffery *et al.*, 2001). The SILO database has been constructed using observational data collected by the Australian Bureau of Meteorology and contains both continuous daily climate records for approximately 4600 locations and interpolated daily climate surfaces across Australia at a resolution of 5km^2 (Jeffery *et al.*, 2001). The observed climate data at each of the 4600 recording stations is used in conjunction with the interpolated daily climate surfaces to infill missing daily data at each climate recording station. This process of supplementing observed data with spatially interpolated data has been defined as ‘patching’. At these locations, continuous daily time step records are available for rainfall, maximum and minimum temperature, Class A pan evaporation, solar radiation and vapour pressure for the time period 1 January 1957 till the present (Jeffery *et al.*, 2001). Rainfall represents an exception with data available for each location back to 1890 due to relatively long observational records Australia-wide.

The interpolated climate surfaces are generated using the observed network of recording stations. A thin plate smoothing spline was used to interpolate daily climate variables, other than rainfall, with ordinary kriging and normalisation used to interpolate daily and monthly rainfall (Hutchinson *et al.,* 1993; Jeffery *et al.*, 2001). The production of these climate surfaces for the whole of Australia has allowed the extraction of climate data at a number of independent latitude and longitude locations for use in a range of biophysical models, but due to the interpolation and smoothing this patched record is not appropriate for examination of local and regional climate trends.

A number of approaches currently exist to assess climate trends. Simple linear regression of the climate variable against time is frequently used (for example in the STARDEX climate analysis package: Peterson *et al.* 2003). This approach is particularly appropriate where there is no expectation of a non-linear trend and where there are unlikely to be other interacting climate factors. Inspection of the residuals can be used to assess for non-linearity in the underlying data and if this exists, then a non-linear relationship can be used as a descriptive relationship. Where there are anticipated interactions between climate variables a multiple regression approach can be used to remove the effect of the interacting factors and the residuals assessed for trends over time (Nicholls 2003). This approach has been used by Nicholls (2003) and Karoly and Braganza (2005a,b) to remove the effect of rainfall on temperatures at national and regional scales.

More sophisticated approaches are possible that include the influence of other factors such as ENSO and decadal variability. For example, the study of Meinke et al. (2004) used several statistical analyses to assess climate and yield trends at sites in eastern Australia, taking account of the effects of ENSO, decadal climate indices, lag effects and soil moisture at sowing. They found that the trend effect was rarely significant by itself but was often a significant part of a broader suite of predictor variables. We examined this approach using the Southern Oscillation Index (SOI), to examine if this indicator could be used effectively to clarify some of the historical trends in climate variables such as maximum temperature or rainfall. However, we found that there was little benefit from this approach. For example, whilst maximum temperature at Jandowae was highly correlated with SOI and rainfall (r^2=0.52) there was no trend in the residuals with time. Similar results were found when considering decadal variability (measured by the Decadal Pacific Oscillation).

In considering which analytical method to use in this study, we need to consider the end use: farmers engaging in discussions which deliver results that they can understand for the analysis of both historical and future climates. Furthermore we are also interested in developing climate change projections based on these trend analyses. Inherently, lag effects, decadal oscillations and ENSO changes are unable to be projected with our current understanding of ocean-atmosphere interactions.

Hence, for this analysis we use the same procedure as Nicholls (2003) to remove the influence of rainfall on temperature (Figure 4).

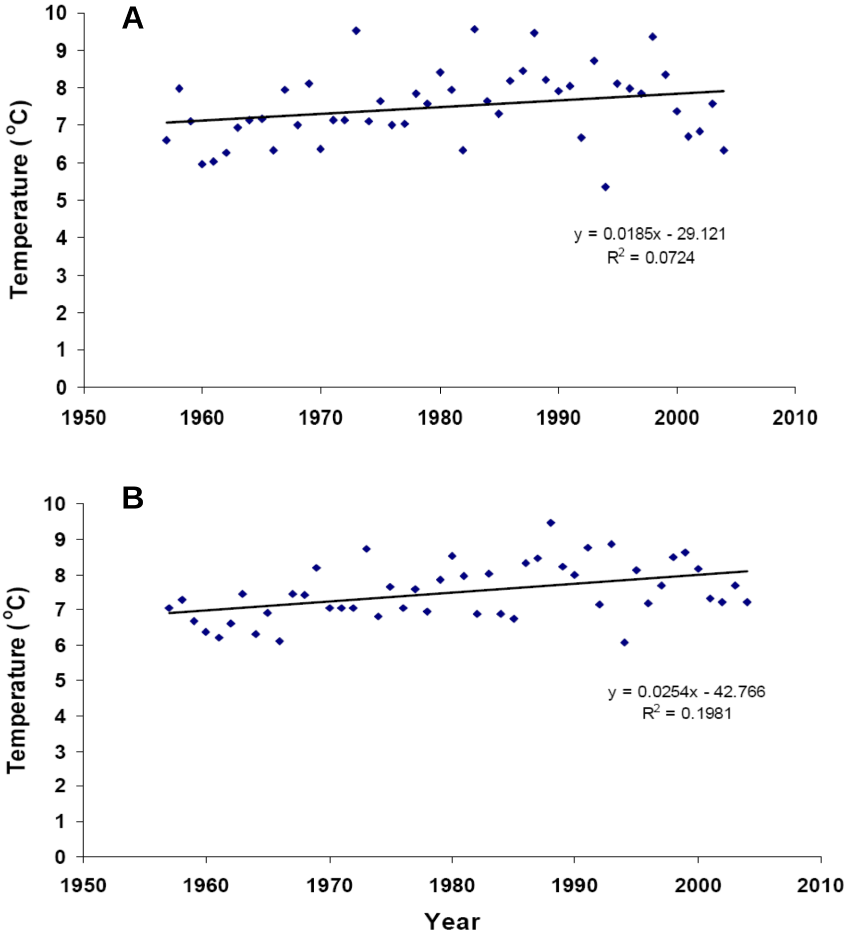


Figure 4: *Jandowae May-Oct minimum temperatures a) as recorded, or b) with the effects of rainfall variation removed.*

There are a large number of possible climate variables that can be analysed for trends: means, ranges, deciles, intensities, return periods, sequence lengths. Following our earlier Milestone Reports, we have restricted the reporting results here to variables that *a priori* are likely to have some direct impact on yields and also to relationships that are statistically significant to at least the 5% level (with a few exceptions which are identified in the text). We have also expressed temperature and rainfall changes in rates per decade. We have restricted ourselves to climate data post 1957 due to the inconsistencies between the quality of the data sources for rainfall (long term daily data) and temperature (often daily data from 1957 onwards but interpolated daily values from monthly averages pre-1957). In developing the climate files, following Meinke et al. (2004), we have produced a climate record that is a composite of climate stations within a 40km radius of the target site and sourced the climate files from the from SILO data archive.

Climate change scenario development

Using future climate scenarios in biophysical models requires some form of post processing. APSIM requires daily climate information for a range of climate variables. In many cases GCM based scenarios are expressed as annual or monthly changes relative to a baseline period. Daily climate change projection data can be derived in many different ways including modification of historical climate records, using historical records to 'seed' a weather generator that then includes climate changes in the output weather files, downscaling of GCM (Global Climate Model) results, and direct use of GCM outputs or broad scenarios of change.

Each of these has its own set of issues (see IPCC 2001, 2007 for discussion). In this study, we are interested not in possible climates of say the year 2100 but rather in assessing what climate conditions farmers in these three regions may have to deal with over the forthcoming 20 to 50 years. Many of the approaches above are not suited to this relatively short time-frame.

Instead, we have developed an approach that modifies historical daily climate files based on a combination of GCM climate scenarios and historical trends in the distribution of climate extremes (i.e. 10th 50th and 90th percentile daily events).

The OZCLIM scenario generator developed by CSIRO Atmospheric Research and the International Global Change Institute (http://www.cmar.csiro.au/ozclim) was used to generate scenarios of future temperature and rainfall change. OZCLIM generates future climate change scenarios based on 12 different GCMs and eighteen different greenhouse gas emission projections (IPCC, 2001). In this way it represents a comprehensive range of future climate uncertainties for use in climate change impact and adaptation research.

In OZCLIM, regional scenarios are generated by linearly regressing the local seasonal mean temperature (or rainfall) against global average temperature, in order to generate, at each grid point, a change (e.g. regional temperature or rainfall) per degree of global warming. The grid point values can then be mapped to obtain a pattern of response that can be scaled according to an estimate of total global warming (Figure 5) (Whetton *et al.,* 2001).

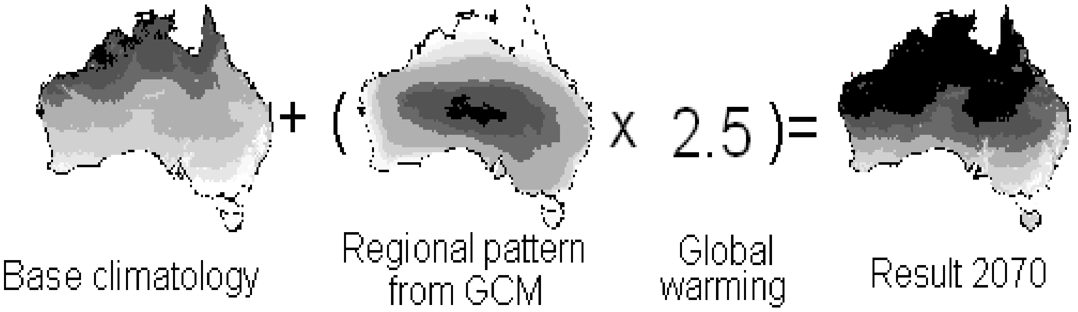


***Figure 5**: Schematic representation of the method employed to generate regional climate change projections (maps are indicative only). The global warming value of 2.5 represents the best estimate of warming for the 2070 period based on a mid range emission scenario. (modified from Whetton et al., 2001).*

The future climate change scenarios are thus very strongly related to the extent of future global warming as well as the pattern of change determined by the climate model examined. For the purposes of this project we wished to sample across both of those elements of uncertainty. In order to do this we examined the different patterns of change from two climate models (i.e. the Hadley Centre (HADCM3.1) and CSIRO (MARK3) models). The second source of uncertainty is a function of the extent of future global warming. This is driven explicitly by the rate at which greenhouse gasses accumulate in the atmosphere over time. For the purposes of this research we have examined three global warming trajectories aligned with 'low', 'mid' and 'high' emission scenarios (Figure 6).

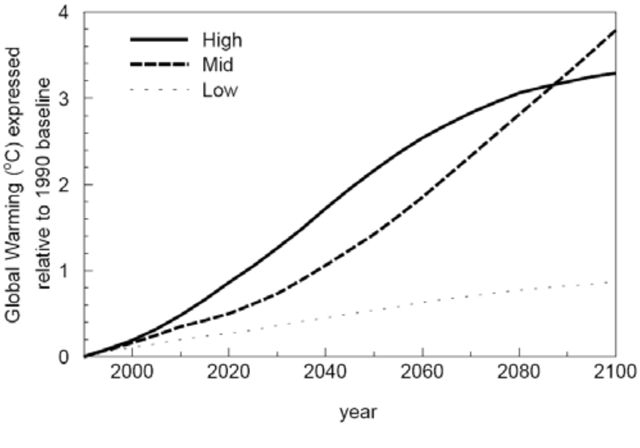


***Figure 6**: Annual global warming values for the 'high', 'mid' and 'low' scenarios relative to 1990 (after IPCC 2001).*

The Hadley Centre (HADCM3.1) and CSIRO fully coupled MARK3 models were used to generate regional patterns of change due to their skill at adequately capturing key elements of Australia's large scale climatic features. The so-called model skill was assessed by examining the degree of correspondence between regional observed and simulated ("hind-cast") patterns of temperature, mean sea level pressure (MSLP) and precipitation (Whetton *et al.,* 2001) measured by root mean square (RMS) error and pattern correlation statistics (Figure 7) (Whetton *et al.,* 2005). Models which generated values of RMS close to zero and pattern correlation values of close to one (top left hand side of the graphs in Figure 7) were seen as adept at capturing both circulation and seasonal patterns of temperature.

In the case of both the HADCM3.1 and the MARK3 models, the degree of correspondence between regional observed and simulated patterns of temperature, mean sea level pressure (MSLP) and precipitation was amongst the highest of all models available from OZCLIM (Figure 7). Both models perform well during the Australian summer (DJF) and autumn (MAM) periods and less well in winter (MJJ) and spring (SON) (Figure 7).

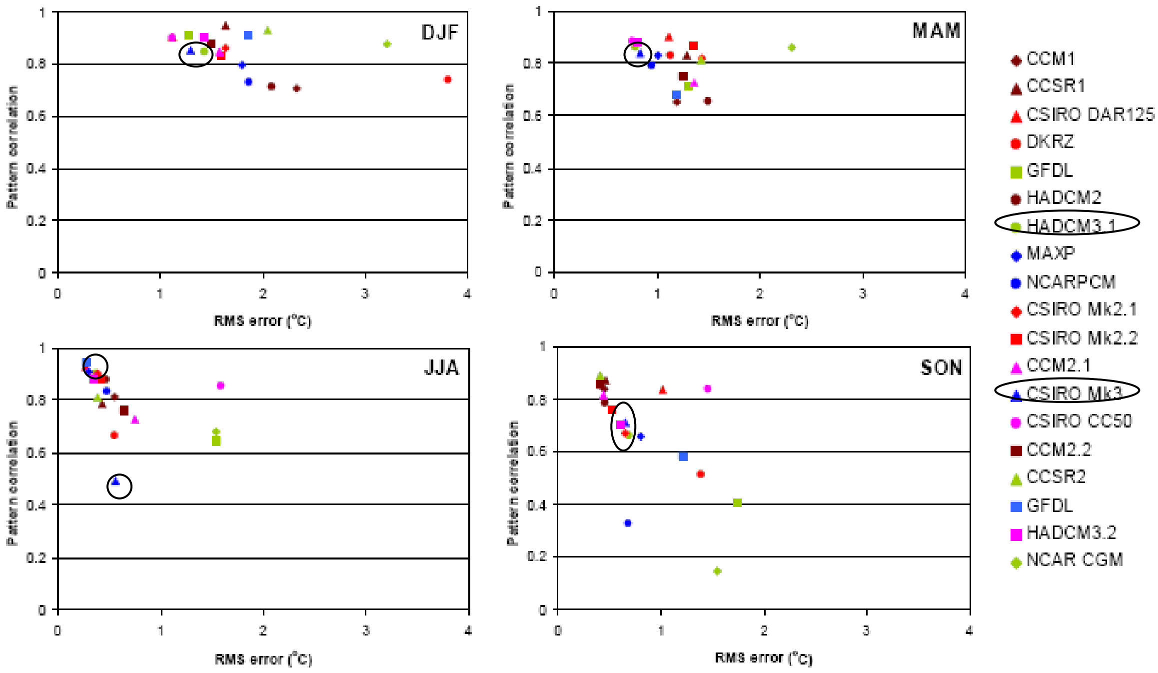


***Figure 7:** Seasonal skill estimates of RMS and pattern correlation values for MSLP calculated over the region 110 to 160°E and 10 to 45°S in 19 climate models for December to February (DJF), March to May (MAM); June to August(JJA) and September to November (SON).*

Patterns of regional change in mean annual temperature (^{o}C) and annual rainfall (%) per degree of global warming were extracted from both the HADCM3.1 and MARK3 GCMs (Figure 8). The patterns of regional warming were greater for the Mark3 GCM (Figure 8d) than for HADCM3.1 however the pattern of rainfall change was greater for the HADCM3.1 GCM over the western half of Australia (Figure 8a).

The regional patterns of change were scaled using a ‘low’ future emission trajectory (IS92c) and ‘medium’ emission trajectory (A2) and a ‘high’ emission trajectory (A1T) for both 2030 and 2070 (Figure 6) (SRES, 2000). These emission scenarios were used to examine a range of possible future global warming scenarios and thus sample across the uncertainty that exists with regard to the future extent of global warming (Table 2).

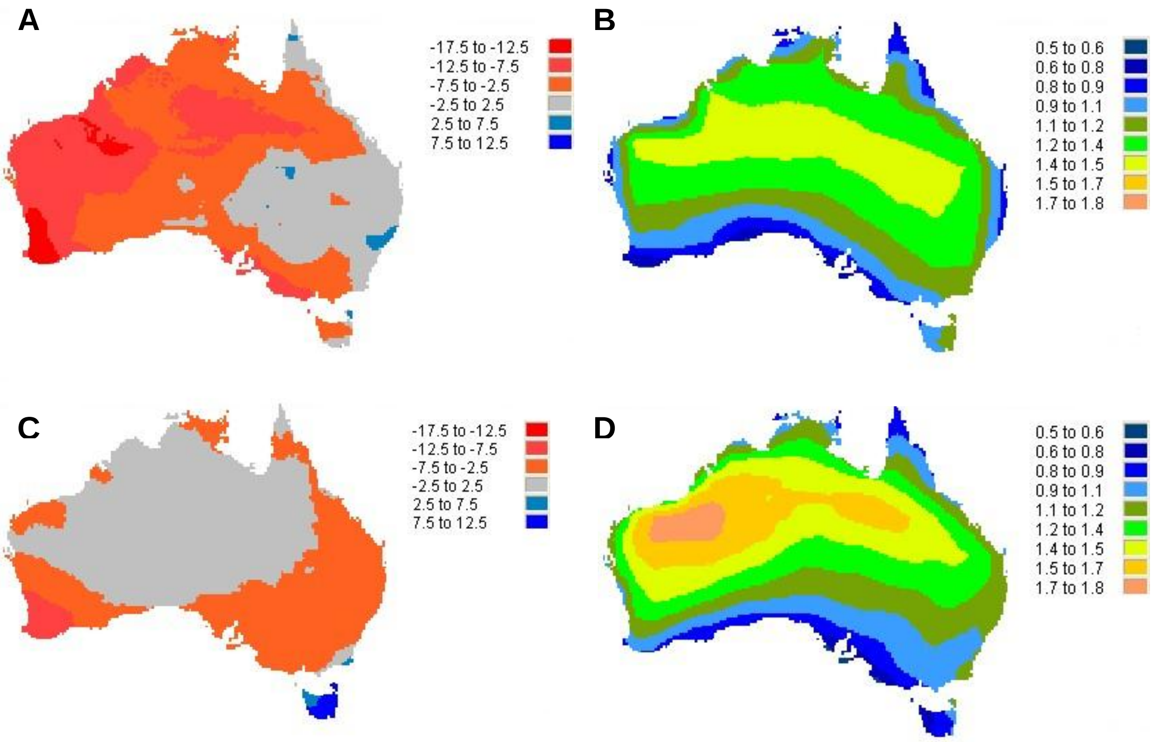


Figure 8: *Regional patterns of a) rainfall (% change from 1990 baseline) and b) average temperature (^{o}C difference from 1990 baseline) per degree of global warming for the HADCM3.1 climate model; Regional patterns of c) rainfall (% change from 1990 baseline) and d) average temperature (^{o}C difference from 1990 baseline) per degree of global warming for the MARK3 climate model.*

Table 2 *Degree of global warming based on IS92c, A2 and A1T emission scenarios for 2020 and 2030.*

Year	Δ Global Temperature (IS92c)	Δ Global Temperature (A2)	Δ Global Temperature (A1T)
2030	+0.41	+0.73	+1.26
2070	+0.81	+2.33	+2.83

By adding the projected warming at 2030 or 2070 (Table 2) to the pattern of warming from either climate model (Figure 8) we developed a range of plausible change for both regional temperature and rainfall (Figure 9). Once these regional changes were calculated and extracted on a monthly basis they were used to scale daily historical climate data for a range of climate stations in each of the three study regions.

Developing daily climate change projections

The methodology used to translate monthly GCM projections to daily climate information in a form usable by APSIM follows that described in Crimp *et al*., 2002. In this approach daily historical climate data are transformed by both identified climate trends and GCM-derived projections. The major steps in this process include:

1. Trend detection – changes in the distribution of daily weather events (i.e. 10th, 50th and 90th percentile temperature and rainfall events) were examined for

individual months across the entire record (i.e. all January 1st days for the period 1975 to 2006);

2. Extrapolation of statistically significant trends out into the future for 2030 and 2070;
3. Projection of changes in mean from GCM derived scenarios.
4. Calculation of other climate variables (e.g. evaporation, vapour pressure deficit and solar radiation) using a multiple regression approach driven by local historical interactions between temperature, rainfall and other variables.

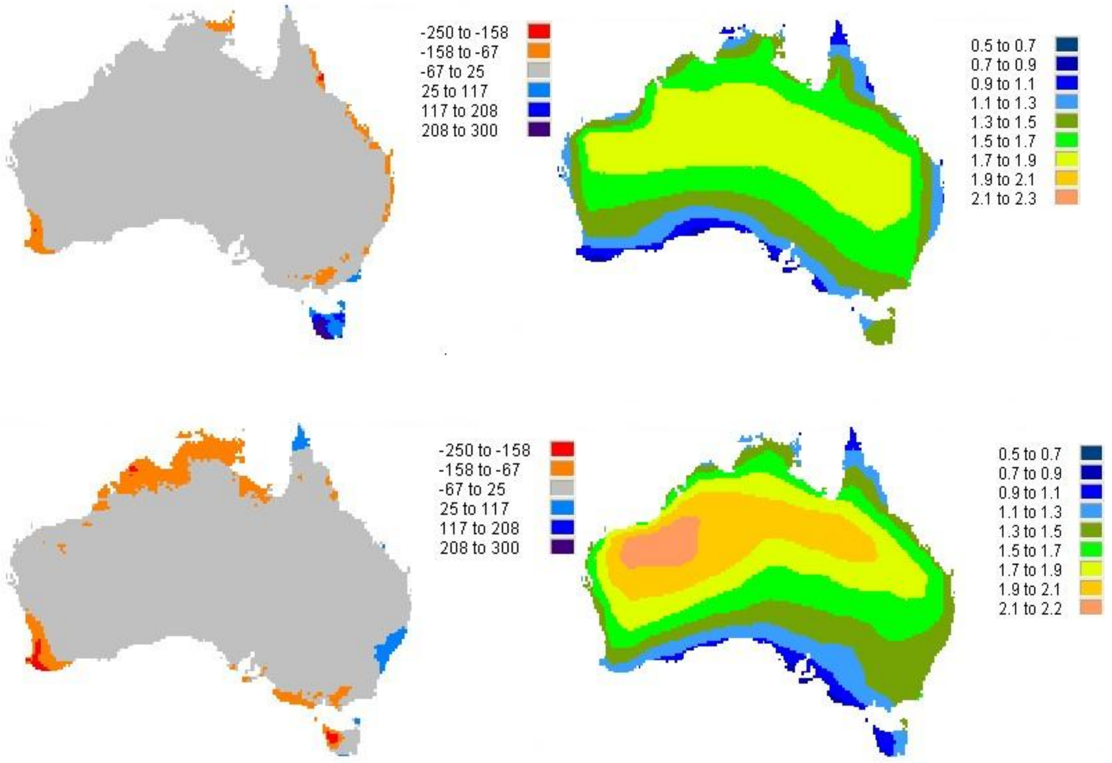


Figure 9: *Regional patterns of (a) rainfall (mm change from 1990 baseline) and b) average temperature (°C difference from 1990 baseline) at 2030 for the A1T 'high' emission scenario and HADCM3.1 climate model; Regional patterns of (c) rainfall (mm change from 1990 baseline) and d) average temperature (°C difference from 1990 baseline) at 2030 for the A1T emission scenario and the MARK3 climate model.*

Trend detection

The scarcity of long term observed climate data is a significant limiting factor in regional detection and attribution studies (Trewin, 2001). A limited amount of long term high quality climate station information is maintained by the Commonwealth Bureau of Meteorology, however, these 100 stations are well dispersed and in some instances did not occur in the case study regions. For this reason secondary climate station information was examined.

The SILO climate data archive (Jeffery *et al*., 2001) provides daily climate data for a range of variables including mean, maximum and minimum temperature, rainfall, vapour pressure, solar radiation and evaporation. Where observed data were not recorded on any one day regionally averaged data were used, a process known as infilling. A selection process to identify both long term temperature and rainfall recording stations with limited missing data was implemented. SILO provides explicit measures of length of record as well as data homogeneity. These measures were used to determine appropriate sites to use for the regional trend analyses. An example of the availability and quality of temperature recording stations for the Jandowae case study region is contained in Figure 10.

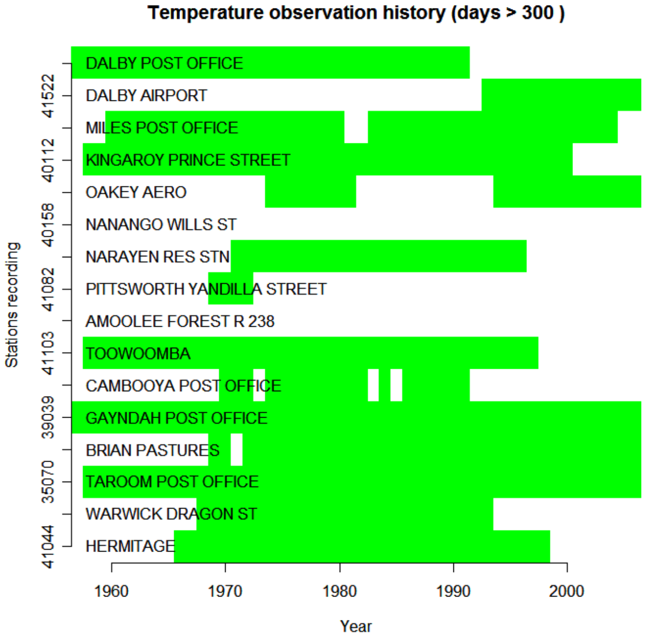


Figure 10: *Recording history of temperature stations in order of increasing distance from the Jandowae study region in Southern Queensland.*

Projection of changes in dispersion

Once suitable stations for a region were identified, a quantile regression approach was used to determine changes in dispersion of daily temperature (i.e. minimum and maximum) and rainfall. The monthly 10th, 50th and 90th *quantiles* - by a *quantile*, we mean the fraction (or percentage) of information below a given value. That is, the 0.1 (or 10%) quantile is the point at which 10% of the data fall below and 90% fall above that value. Temperature and rainfall were used to develop a simple linear regression model over the 1975 to 2006 period. Significant trends ($p > 0.95$) in these temperature and rainfall quantiles were extrapolated forward to 2030 and 2070 in order to modify the distribution of daily events. These modified distributions are displayed as cumulative distribution functions (CDF). The CDF, also called ‘probability distribution function’ or just ‘distribution function’, completely describes the distribution of data in a population. Figure 11 demonstrates the trend detection, extrapolation and modification of daily time series information for September minimum temperatures recorded at Emerald for the period 1970 to 2006. Figure 11b highlights the modification of the CDF and Figure 11c highlights the development of the new daily time series for September.

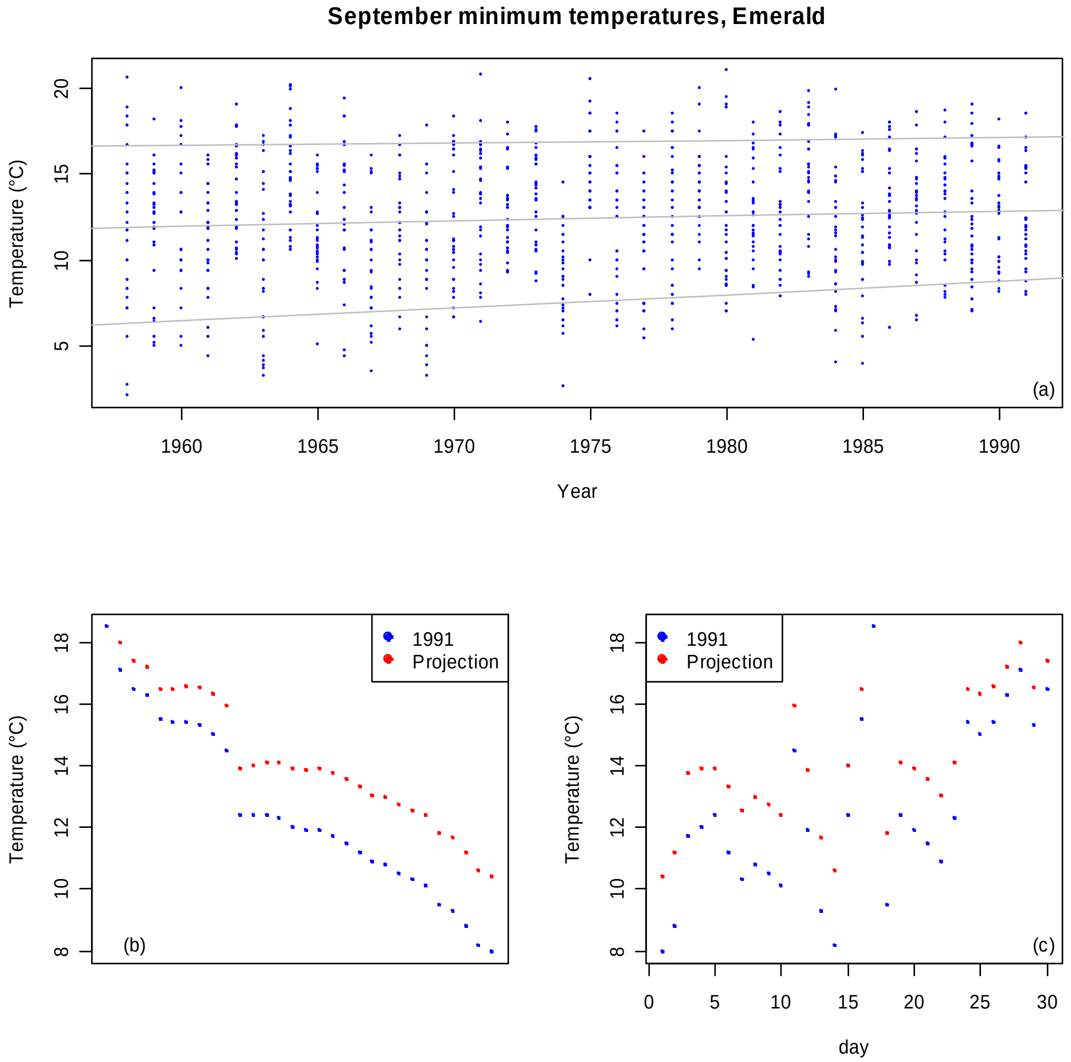


Figure 11: *a) trends of quantile 10, 50 and 90; b) CDF of minimum temperature and projection, and c) time series of the same for September minimum temperatures recorded at Emerald for the period 1970 to 2006.*

Projection of changes in mean

Monthly OZCLIM projections of mean temperature and rainfall were applied to the modified series in order to shift the distribution in line with the projections from each of the models and emission scenarios analysed.

Ancillary model variables

Correlations between maximum temperature, rainfall and the other climate variables (i.e. evaporation, vapour pressure and solar radiation) were determined at each location in order to develop simple multiple regression relationships to generate modified variables once temperature and rainfall changes had been applied. The correlation between maximum temperature and each of the other climate variables is presented in Table 3. These correlations suggest this approach is robust as variation in maximum temperature alone can account for between 61 to 80% of the variability in evaporation, vapour pressure or solar radiation data, with only vapour pressure in WA showing a poor correlation (i.e. 41%). The inclusion of rainfall as a component of the multiple regression relationship improved correlations by between 15 and 25% (not shown).

***Table 3**. A matrix of correlation coefficients (r) of maximum temperature and evaporation, radiation and vapour pressure at state level(ρ=0.001) after crimp et al., 2002.*

Location	Evaporation (r)	Radiation (r)	Vapour Pressure (r)
VIC	0.80	0.70	0.64
WA	0.81	0.69	0.41
QLD	0.76	0.67	0.61
Australia	0.78	0.69	0.57

Parameterisation of APSIM

In agricultural systems, many approaches have already been developed to examine the likely impacts of both climate variability and change on crop production (Hammer *et al.*, 2001; Meinke and Stone 2005; Potgieter *et al.*, 2008). In this project we have used the **A**gricultural **P**roduction **S**ystems s**IM**ulator (APSIM) to assess likely changes in crop yields in response to both climate change and adaptive management. This model was used as it has been extensively applied and validated for Australian farming systems and has a flexible management interface which lends itself to examining and evaluating adaptive on-farm management (Keating *et al.,* 2003).

The APSIM modelling framework is made up of:

1. "A set of biophysical modules that simulate biological and physical processes in farming systems.
2. A set of management modules that allow the user to specify the intended management rules that characterise the scenario being simulated and that control the simulation.
3. Various modules to facilitate data input and output to and from the simulation.
4. A simulation engine that drives the simulation process and facilitates communication between the independent modules" (APSRU, 2006).

APSIM requires daily climate records that include maximum and minimum temperature, rainfall, vapour pressure, evaporation and solar radiation. These records are sourced either from the nearest weather station, farmer records or interpolated climate data obtained from the Qld NRW/BoM SILO climate data archive (Jeffery *et al.,* 2001). Individual farmer records, particularly for rainfall, are valuable as rainfall can vary significantly in a spatial sense even within a local area. Analysis of the weather data for the three regions of interest in this study have been undertaken using a range of approaches to assess irregularities, non-homogeneities and climate trends (Karoly and Braganza 2005a,b; Meinke *et al.,* 2004; Nicholls 2003; Peterson *et al.,* 2003).

Detailed site selection, model calibration and benchmarking activities have been documented in previous reports and so have not been include in the final report. Examples of benchmark results (i.e. simulated versus observed crop yields) at three sites have been included for indicative purposes only (Figures 12, 13, 14). Benchmarking was continued at each site until simulated and observed crop yields showed less than ten percent variation.

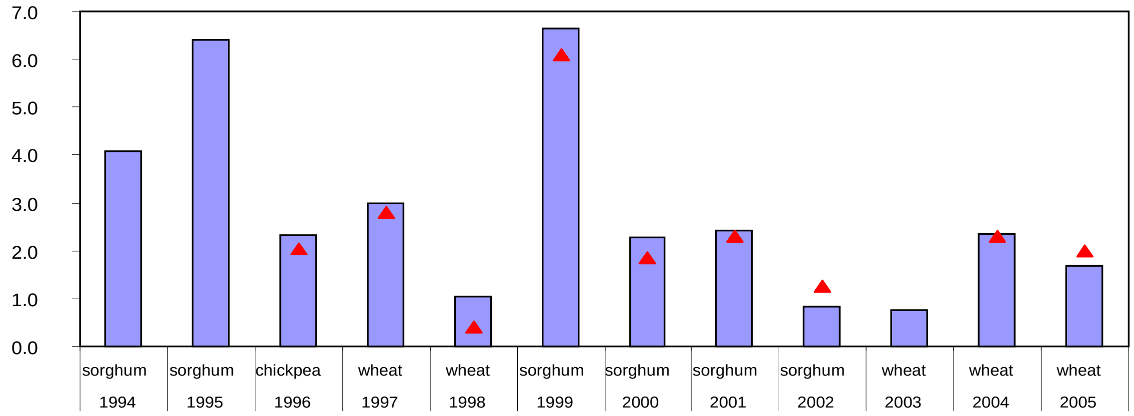


Figure 12: *Comparison of simulated versus observed sorghum, wheat and chickpea yields for a case study farm in the Jandowae region for the period 1994 to 2005. Measured yields represented by shaded triangles.*

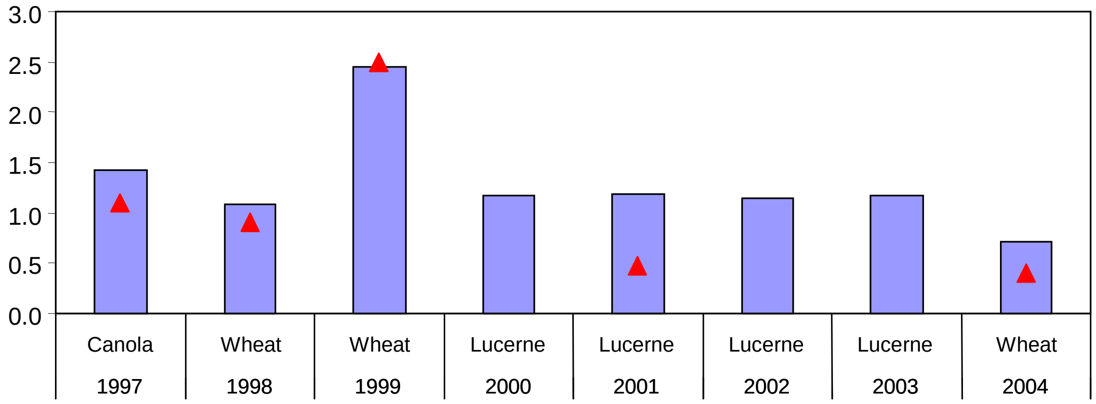


Figure 13: *Comparison of simulated versus observed canola, wheat and lucerne yields for a case study farm in the Birchip region for the period 1994 to 2005. Measured yields represented by shaded triangles.*

Model parameterisation required for simulation of soil water, soil N and organic matter balances were determined on a site-by-site basis consistent with observational data (where available) and expert farmer knowledge (Crimp *et al*., 2008). Relevant soil parameters were not reset annually in the model simulations but allowed to impact on the soil and soil water dynamics in following seasons. In this way a more accurate representation of the impact of climate and management interactions was attained. Sowing windows varied across all sites with sowing conditional on receipt of sufficient planting rains (i.e. between 10 and 25 mm of rain over a 3 day period depending on farm). Seeding rates and fertiliser management were determined at each site based on information provided by the farmer.

In total, APSIM was used to simulate the interaction between climate, soils, farm management and production at 13 locations across the three study regions. Three sites were chosen in the Jandowae region (i.e. the farms of Terry Dalgliesh, Barry Gourley and Neil Wegener), five sites were chosen in the Birchip region (i.e. the farms of Ian McClelland, Peter Funcke, David Smith, Paul Barclay and Geoff and Bronwyn Hunt) and five sites were chosen in the Mingenew region (i.e. the farms of

Donald Heitman, Chris Gillam, Kevin and Betty Heitman, and John Holmes). For purposes of anonymity a simple numbering convention will be used when discussing the results from each farm.

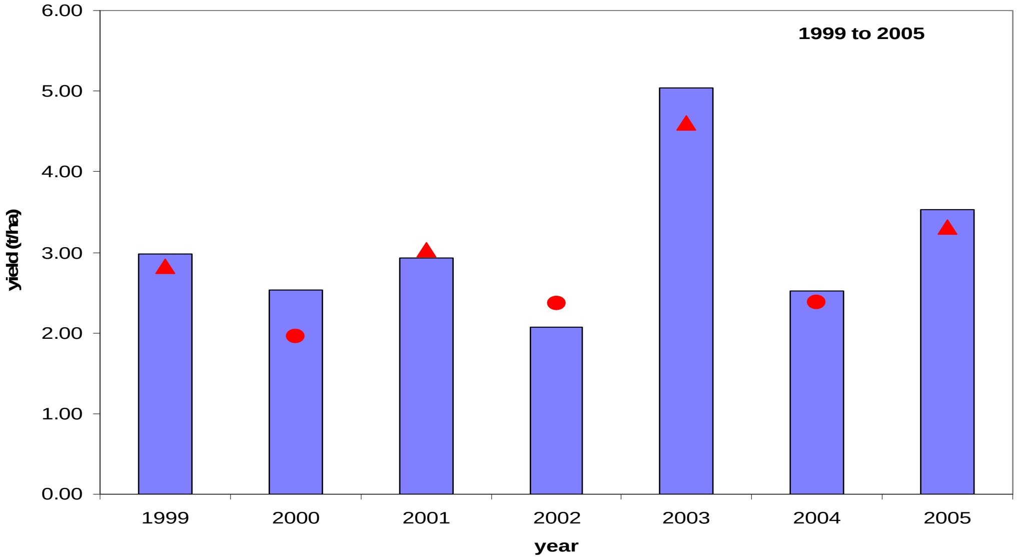


Figure 14: *Comparison of simulated versus observed wheat and lupin yields (tonnes per hectare) at a farm in the Mingenew region for the period 1999 to 2005. Measured wheat yields are represented by shaded triangle and measured lupin yields represented by shaded circles. Simulated wheat and lupin yields are represented by blue bars.*

Through the series of regional workshops and individual interviews a number of tactical adaptation options were identified. There was significant commonality between the three regions in regard to the adaptation options identified (i.e. common adaptation options highlighted in Table 1). Management adaptations included changes in planting dates, crop rotations, crop density, crop variety, fertilisation and stubble management.

Quantifying the impacts of climate change on spraying opportunities

In addition to evaluating tactical adaptation options identified by farmers, we also considered examining the impacts of changing temperature and relative humidity on spraying opportunities (i.e. herbicide, pesticide, fungicide spraying).

The analysis undertaken in each of the three regions examined current optimal times for herbicide spraying (as a function of appropriate temperature and relative humidity conditions) as well as the impact that climate change may have on these optimal spraying windows.

Daily climate data (maximum and minimum temperature and vapour pressure were extracted from the SILO data base (Jeffrey *et al.,* 2001) and the difference between the drybulb and wetbulb temperatures (i.e. Delta T – henceforth ΔT) was calculated using established methods (BoM 2004). ΔT is an important indicator for acceptable spraying conditions as it affects spray evaporation rate and droplet lifetime. In particular, high values of ΔT will result in short droplet lifetime and low efficacy when using low volume spraying equipment. Guidelines in Australia suggest that when spraying, ΔT should not be above 8 and this threshold was used to classify days in the historical record that were unsuitable for spraying (Figure 15). Wind speed is also logistically important to spraying operations with both high winds and low wind (via atmospheric inversions) being associated with spray drift problems. In terms of wind speed generally accepted guidelines in Australia are to avoid spraying with wind speeds greater than 15km/hr and less than 3km/hr (BoM 2004). In these analyses changing wind conditions were not considered.

The likely impacts of climate change on spraying conditions within the three study areas was determined by modifying the observed daily climate record with monthly climate change scenarios generated from the Mark3 GCM using the A1T (‘high’) and B1 (‘low’) emission scenarios for 2030 and 2070.

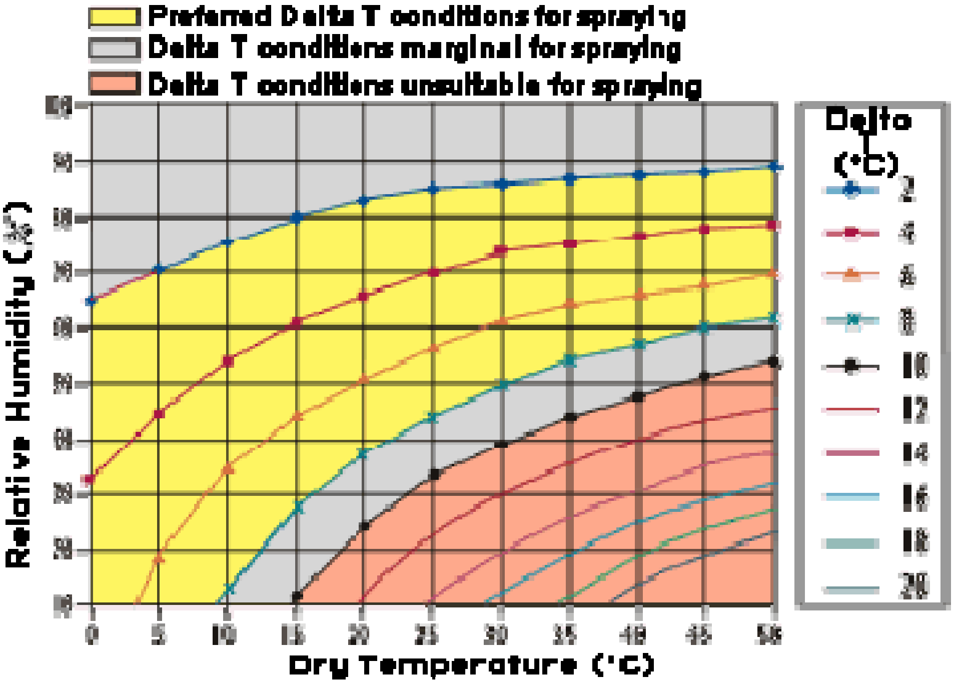


***Figure 15**: Relationship between relative humidity (%) and dry bulb temperature (^{o}C) for Delta T values ranging from 2 to 20^{o}C. Optimal spraying conditions (not considering wind) exist between the Delta T values of 2(blue dotted line) to 8^{o}C (light blue hatched line).*

RESULTS

Climate trends

Jandowae Region

Annual mean temperature has increased at a rate of 0.16°C/decade but the rate of warming has been much faster in the winter six months (May to October: 0.22°C/decade) than in summer (November to April: 0.13°C/decade). Annual maximum temperatures increased by 0.18°C/decade. As with mean temperatures, the rate of increase has been faster in the winter six months (May to October: 0.25°C/decade) than in summer (November to April: 0.15°C/decade). Even though maximum temperatures have increased on average, there has been no significant increase in the hottest day of the year.

Annual minimum temperatures increased by 0.18°C/decade. As with mean and maximum temperatures, the rate of increase has been faster in the winter six months (May to October: 0.25°C/decade) than in summer (November to April: 0.11°C/decade). Even though minimum temperatures have increased on average, there has been no significant change in the temperature of the coldest night of the year. The trend towards warmer nights has been tracked by a trend to higher dewpoint temperatures with these increasing rapidly in the winter six months (0.3°C/decade) but with no significant change (0.07°C/decade) in summer.

There has been a significant reduction in the number of frosts per year (-1.9 frosts/decade) when the effects of rainfall variation are removed. This has been associated with weak trends towards later starts to the frost season (0.23days/decade) and earlier finishes (-0.22days/decade) (Figure 16). These changes have resulted in a significant reduction in the period over which frost occurs (-5.1days/decade). Most of these changes are due to the increases in minimum temperatures in winter.

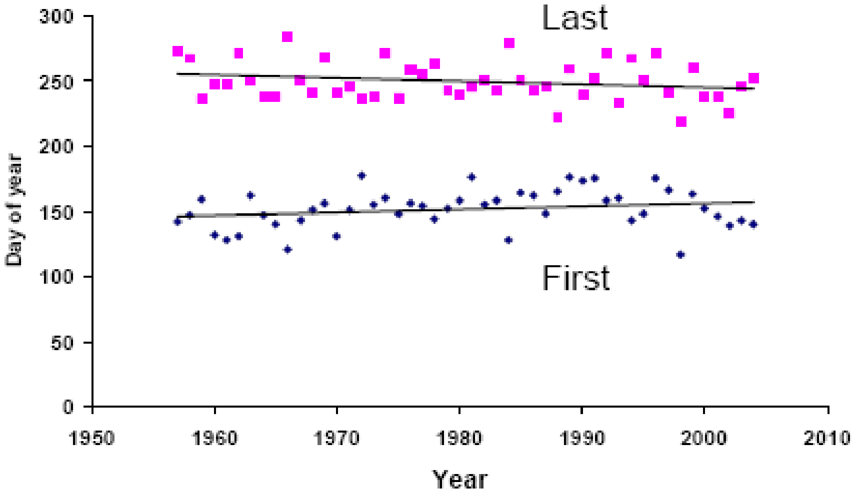


Figure 16: *Date of occurrence (day of the year) of the first and last frosts in the Jandowae region 1957 to 2004.*

Whilst there appears to be a declining trend in annual rainfall (-17.5mm/decade), this is not statistically significant due to high year-to-year variability. The decline seems to be occurring equally across summer and winter. There is a trend towards an increase in the number of raindays each year (0.31days/decade) with most of this change occurring in the winter six months (0.26days/decade).

If the general trend towards lower rainfall is allowed for, the trend towards more raindays is even stronger (3.6 days/decade). As a result of both trends towards lower rainfall and more raindays, rainfall intensity (rain per rainday) is reduced at annual (-0.22mm/day/decade), winter (-0.33mm/day/decade) and summer (-0.19mm/day /decade) timescales. To put these in perspective, the average values for rainfall intensity (1957 to 2004) are 5.1, 3.8 and 5.2 mm/day for annual, winter and summer periods respectively.

Calculated atmospheric vapour pressure has increased (0.13hPa/decade). The increases have been significant in winter, especially when the effects of rainfall variation are removed (0.23hPa/decade). To put this in perspective, the winter average is 11.7hPa. Most of this increase in vapour pressure is associated with increased minimum temperatures. Similarly, if the effects of minimum temperatures are removed, there is an underlying increase in vapour pressure deficit (0.26hPa/decade) whereas there is otherwise no trend.

Birchip Region

Annual mean temperature has not significantly changed in Birchip over the past five decades (0.02°C/decade). Winter mean temperatures have increased by 0.05°C/decade but this also was not statistically significant. Annual maximum temperatures increased by 0.08°C/decade (not significant). As with Jandowae, the rate of increase has been faster in the winter six months (May to October: 0.09°C/decade) than in summer (November to April: 0.06°C) but in this case, the trends were not statistically significant. There were also no significant changes in the hottest day of the year.

Annual minimum temperatures decreased by -0.02°C/decade (not significant) and there were small but not significant reductions in winter and summer minimum temperatures (-0.01 and -0.1°C/decade) respectively.

The temperature of the coldest night of the year has not significantly changed over the past five decades although the temperature of the coldest night in summer has increased (0.24°C/decade).

There is a strong trend of increase in the date of the last frost (4.9days/decade). This appears to be independent of variations in rainfall or minimum temperatures (Figure 17). This, plus small reductions (not statistically significant) in the date of the first frost have resulted in strong trends to increased frost period (6 days/decade). However, there has been no corresponding increase in the number of frost days.

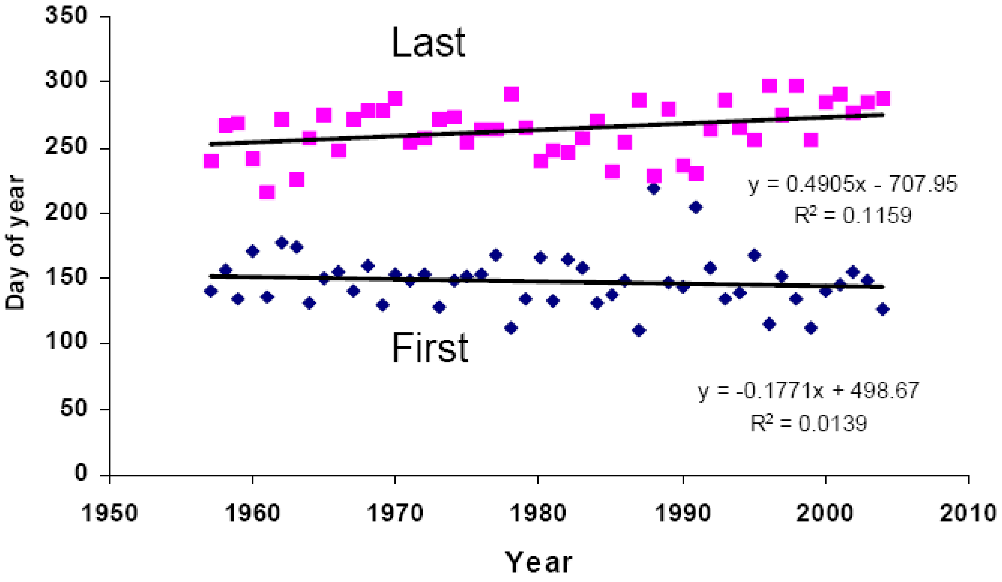


Figure 17: *Date of occurrence (day of the year) of the first and last frosts in the Birchip region 1957 to 2004.*

There are no statistically significant trends in annual or summer rainfall, number of raindays or rainfall intensity. In winter there are weak trends towards increased numbers of raindays (1.9days/decade) and reduced rainfall intensity (-0.4mm/day/decade). To put these figures in perspective, the Birchip region averaged 102 raindays and 2.1mm/day over the past five decades.

Mingenew Region

Annual mean temperature in this region has increased at a rate of 0.1°C/decade but the rate of warming has been much faster in the winter six months (May to October: 0.12°C/decade) than in summer. Annual maximum temperatures increased by 0.12°C/decade. As with mean temperatures, the rate of increase has been faster in the winter six months (May to October: 0.14°C/decade) than in summer (Figure 18b).

Annual minimum temperatures increased by 0.07°C/decade. As with mean and maximum temperatures, the rate of increase has been fastest in the winter six months (May to October: 0.1°C/decade). There has been a slight reduction in the number of frosts per year (-0.02 frosts/decade) however this trend was not statistically significant (Figure 18b). .

Analysis of the climate records in this region showed a statistically significant ($p \approx 0.07$) decline in annual rainfall of -0.2mm/day/decade since 1950 (Figure 18a). Changes in rainfall were not limited to mean climate indices but also to extremes (greater than the 95% percentile) with extreme rainfall events showing declines both annually and during June to August (Figure 18c) and extreme temperatures showing strong warming trends in the June to August period (Figure 18d).

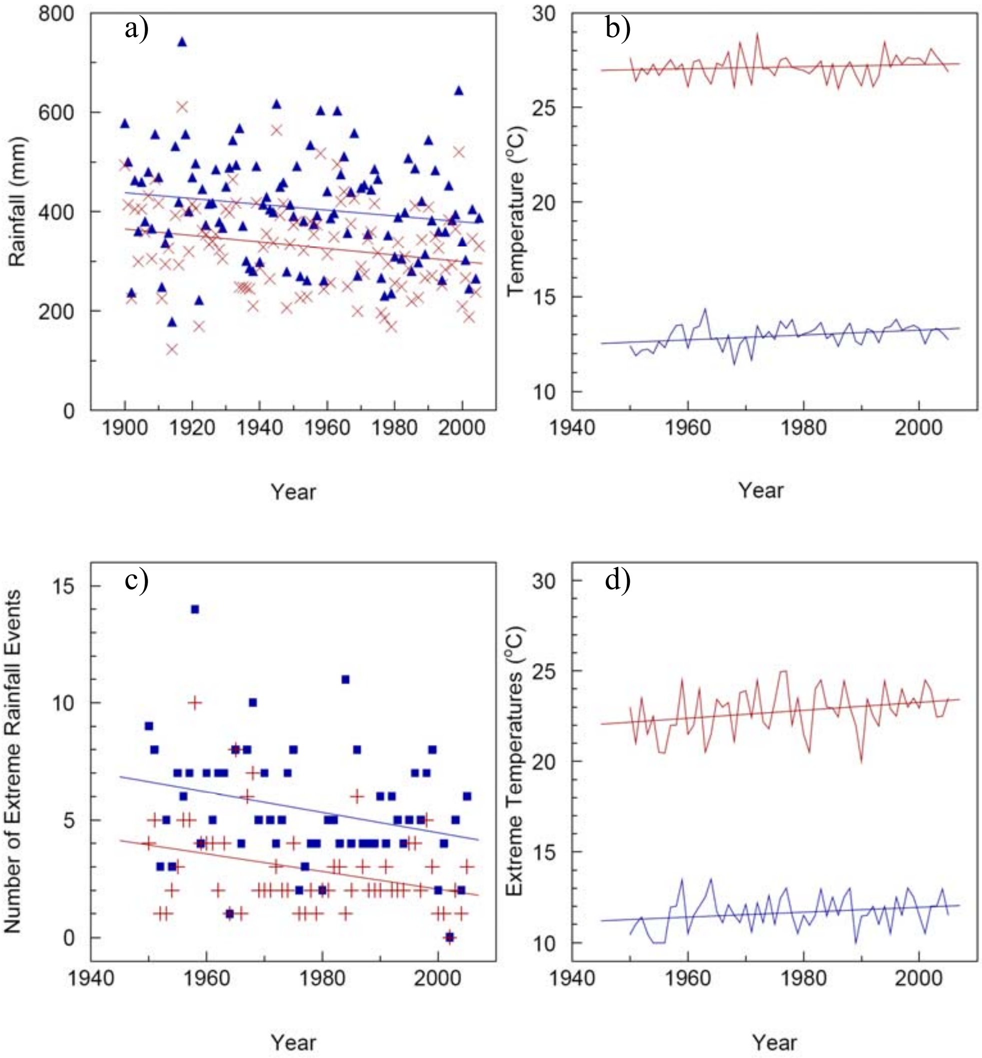


Figure 18 *: a) Trends in annual rainfall (blue) and May to October rainfall (red); b) trends in annual mean maximum temperature (red) and minimum temperature (blue); c) trends in the number of extreme rainfall events annually (blue) and in June to August (red) and d) trends in extreme maximum temperatures (red) and minimum temperatures (blue) for June to August.*

Climate change adaptation results

In the discussions that follow we examine the likely impacts of climate change on crop production in each of the three case study regions At 2030, we consider likely rainfall, temperature and CO_2 changes associated with both 'mid' and high' emission scenarios from two different GCMs (i.e. the HADCM3.1 and MARK3 models) and resultant impacts on crop productivity. We evaluate the effectiveness of a range of tactical adaptation options (see Appendix A) on each farm by comparing long term baseline yields with future yields with or without adaptation options considered. We also evaluate these adaptation options for 2070 using both the HADCM3.1 and MARK3 GCM models; however in this examination we focus solely on the high emission scenario due to the long time-frame and associated uncertainties.

Jandowae Region – 2030

In the Southern Queensland region of Jandowae future changes in rainfall remain uncertain. Under the 'mid' range global warming scenario (i.e. A2 SRES emission scenario) temperatures are projected to increase by 0.6 to 0.9°C by 2030 compared with average 1990 temperature conditions, whereas annual rainfall is projected to decline between 1 and 3% compared to average 1990 rainfall conditions. Ambient CO_2 concentrations of approximately 451ppm are associated with this 'mid' range global warming scenario and have been incorporated in the crop simulations to account for likely reductions in crop transpiration and improved radiation use efficiency under higher CO_2 levels (i.e. the CO_2 fertilisation effect). Under the 'high' range global warming scenario (i.e. A1T SRES emission scenario) local Jandowae seasonal temperatures are projected to increase by approximately 1.1 to 1.6°C by 2030 and annual rainfall is projected to decline by 1 to 5% depending on climate model projections and farm location. Ambient CO_2 concentrations in this scenario are approximately 440ppm, but the concentrations of other greenhouse gasses are higher than for the A2 scenario thus producing greater global warming.

In the case of Farm 1 (predominantly winter cropping and some summer crops) the 'mid' range global warming scenario at 2030 and resultant HADCM3.1 climate change projections produced an increase in median wheat yields of 16% if 'no change' in on-farm management occurred (i.e. a change from 2130kg/ha to 2490kg/ha) (Figure 19). This increase in crop yield is a direct result of a temperature increase of 0.7°C, a 2% reduction in annual rainfall and increased atmospheric CO_2 concentration from 380ppm to 451ppm. This is directly in response to improved water use efficiencies gained from higher CO_2 concentrations outweighing the 2% loss in average rainfall.

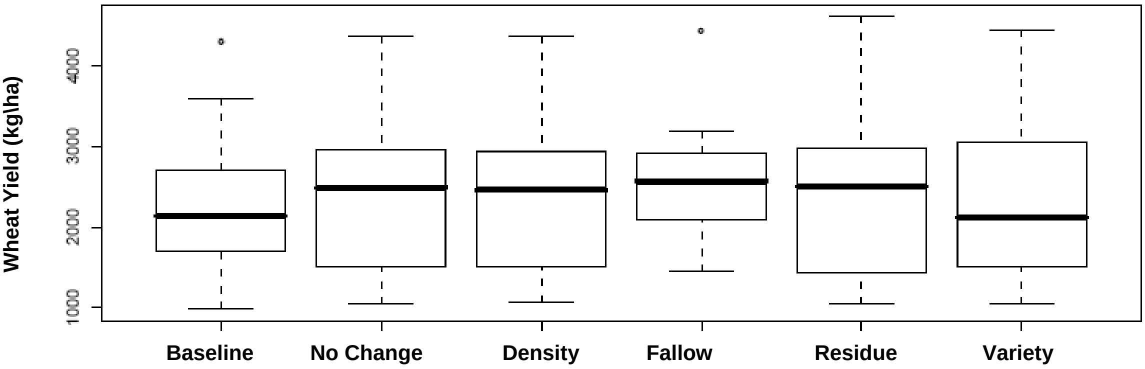


***Figure19**: Jandowae – Simulated wheat yields (kg/ha) for Farm 1 (predominantly winter cropping and some summer crops) under current climate conditions (baseline- 1957 to 2006) compared with simulated wheat yields under 'mid' range global warming scenario and resultant HADCM3.1 model projections for different management options. These include no change in current management 'No Change', reduced planting density 'Density', increasing fallow 'Fallow', increasing residue retention 'Residue' and choosing shorter season varieties 'Variety'. The lower and upper edges of the box represent the 25th and 75th percentile yield values, the black line represents the 50th percentile yield and the upper and lower whiskers represent the 10 and 90 percentile yield values.*

Reducing planting densities (i.e. 'Density') or choosing shorter season varieties (i.e. 'Variety') (see appendix A for more details) resulted in modest declines in median yields compared with the ‘no change’ case (i.e. 2 and 14% respectively) (Figure 19). Introducing a fallow in the crop rotation before wheat proved beneficial at this location, with median yield increasing an additional 4% compared with the ‘no change’ scenario (i.e. 20% increase in median yields compared with the 1957 to 2006 baseline).

Significant improvements in the lowest yields were also attained through the ‘fallow’ adaptation option with the lowest simulated wheat yields rising from 980kg/ha in the baseline simulation to 1450kg/ha (Figure 19). Increasing the proportion of residue retained after harvest also served to improve median wheat yields compared to the ‘no change’ simulation, with a further 1% improvement in median yield. In all cases, except for the ‘Fallow’ adaptation option, wheat yield variability increased in response to warmer and marginally drier conditions.

The yields simulated using projections from the MARK3 model (i.e. 0.6°C warming and 1% decline in rainfall) resulted in a 10% increase in median wheat yield if ‘no change’ in on-farm management occurred (i.e. a change from 2130kg/ha to 2330kg/ha) (see Appendix B, Figure 1). Again these yield benefits are driven by higher CO_2 concentrations and little change in rainfall.

Under the ‘high’ range global warming scenario (i.e. A1T SRES emission scenario – 440ppm, 1.6°C warming and 5% decline in annual rainfall) and HADCM3.1 model projections, median wheat yields for this farming system increased by approximately 6% (Figure 20). Again this was driven largely by higher CO_2 concentrations and small changes in rainfall relative to the baseline. The residue retention adaptive management option provided an additional 2% improvement on median yields compared with the ‘no change’ case (i.e. a change from 2130kg/ha to 2310kg/ha) (Figure 20).

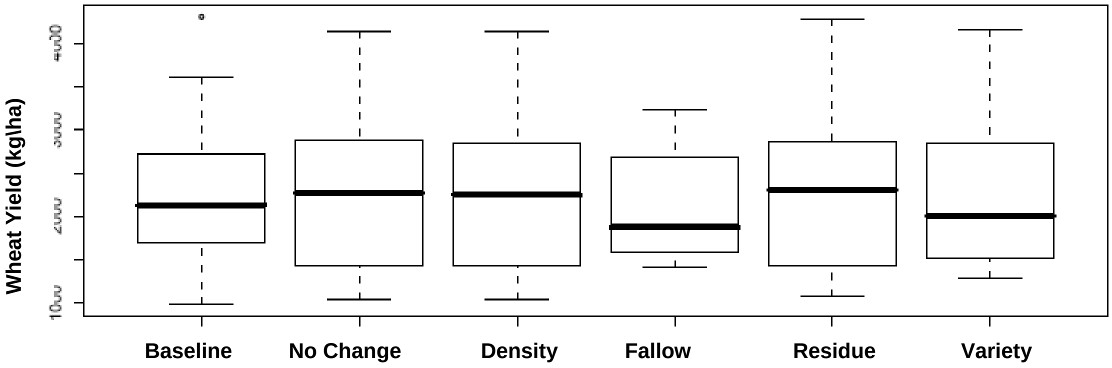


Figure 20*: Jandowae – Simulated wheat yields (kg/ha) for Farm 1 (based predominantly on winter cropping) under current climate conditions (baseline- 1957 to 2006) compared with simulated wheat yields under a ‘high’ global warming scenario and resultant HADCM3.1 model projections for different management options.*

Wheat yield impacts from the MARK3 model projections resulting from the ‘high’ global warming scenario are slightly lower than those from the HADCM3.1 model (see Appendix B, Figure 2). Under this climate change scenario both ‘fallow’ and ‘residue’ provide additional yield benefits of 9 and 4% respectively (see Appendix B, Figure 2).

The second case study farm in this region (Farm 2) was predominantly a summer cropping system with some winter crops (i.e. almost the opposite to Farm 1). The summer crop most frequently grown was sorghum, and thus the focus of the analysis that follows. The 'mid' range global warming scenario at 2030 and resultant HADCM3.1 climate change projections produced an increase in median yields of 8% for the 'no change' in farm management, with additional significant yield benefits from both 'fallow' (i.e. 27%) and 'residue' adaptive management (i.e. 23%). As with Farm 1, the modest warming (i.e. 0.6°C) and slight decline in rainfall (i.e. 3%) are offset by the increase in CO_2 concentration (Figure 21). Both decreasing planting density and varietal change delivered no yield benefits above the 'no change' case (Figure 21)

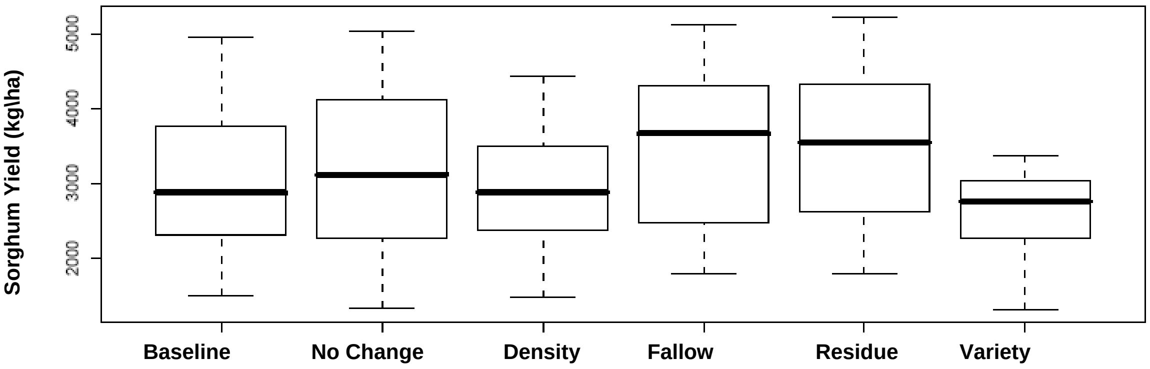


Figure 21: Jandowae – Simulated sorghum yields (kg/ha) for Farm 2(based predominantly on summer cropping) under current climate conditions (baseline- 1957 to 2006) compared with simulated sorghum yields under a 'mid' global warming scenario and resultant HADCM3.1 model projections for different management options

The yields simulated using projections from the MARK3 model (i.e. 0.6°C warming and less than 1% decline in rainfall) resulted in a 5% increase in median sorghum yield if 'no change' in on-farm management occurred (i.e. a change from 2870kg/ha to 3030kg/ha) (see Appendix B, Figure 3). Again these yield benefits are driven by higher CO_2 concentrations and little change in rainfall.

Under the 'high' range global warming scenario (i.e. A1T SRES emission scenario – 440ppm, 1.6°C warming and 5% decline in annual rainfall) and HADCM3.1 model projections, median sorghum yields for this farming system increased by approximately 5% (Figure 22). Again this was driven largely by higher CO_2 concentrations and small changes in rainfall relative to the baseline. The 'residue' and 'fallow' adaptive management options provided additional yield benefits of 15% and 8% respectively (Figure 22).

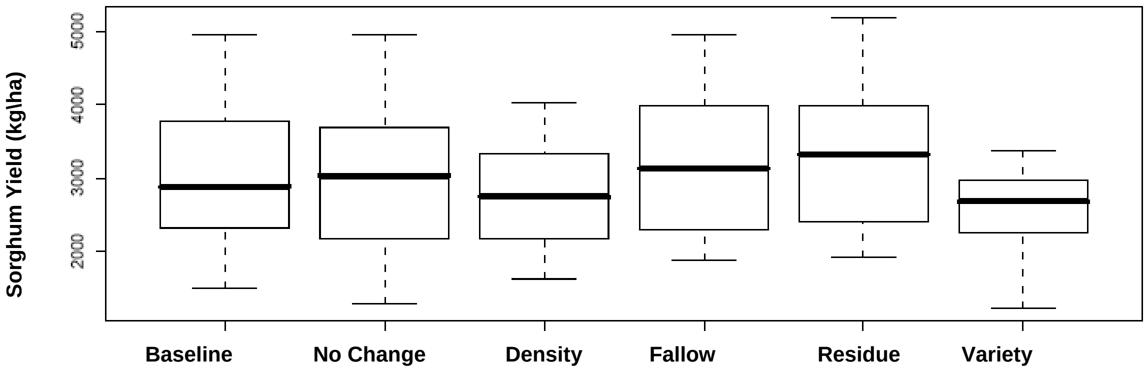


Figure 22: Jandowae – Simulated sorghum yields (kg/ha) for Farm 2 (based predominantly on summer cropping) under current climate conditions (baseline- 1957 to 2006) compared with simulated sorghum yields under a 'high' global warming scenario and resultant HADCM3.1 model projections for different management options

Under the 'high' global warming scenario and MARK3 model projections, median sorghum yields for this farming system fell by 2% for the 'no change' case (Figure 23). The 'fallow' and residue' adaptation options continued to provide yield benefits with 24% and 16% median yield benefits simulated under these climate conditions (Figure 23).

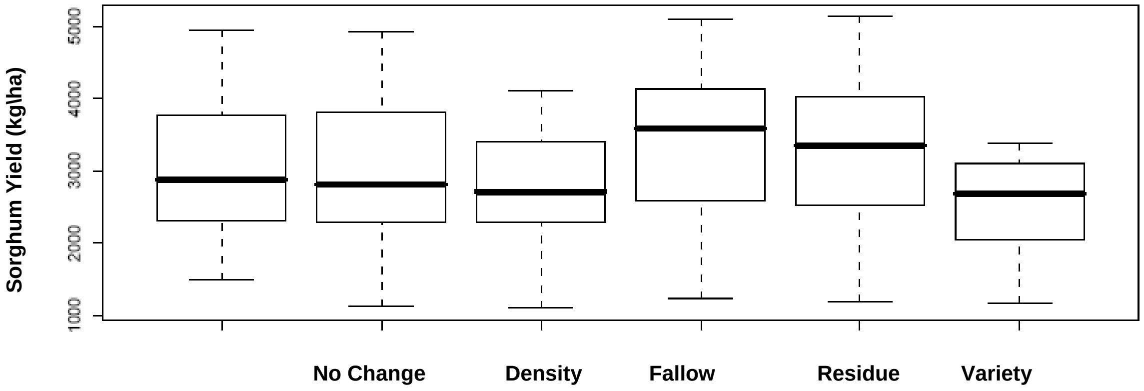


Figure 23: Jandowae – Simulated sorghum yields (kg/ha) for Farm 2 (based predominantly on summer cropping) under current climate conditions (baseline- 1957 to 2006) compared with simulated sorghum yields under a 'high' global warming scenario and resultant MARK3 model projections for different management options

The remaining case study farm in this region, Farm 3, was characterised as a wheat and cotton farming system. For this example we have focused on the winter cropping component of the farming system for the discussion that follows. Under a 'mid' global warming scenario and resultant HADCM3.1 projections median wheat yields increased for all adaptation options considered. In particular 'fallow' and 'residue' management provided significant benefits above the current long term baseline (i.e. 55% and 19% respectively) (Figure 24). The significant yield benefit from the 'fallow' adaptation must be assessed in the context of the impacts on the whole crop rotation. In this instance the farmer suggested adding two additional summer fallows into the rotation (see appendix A). This served to reduce median yield performance of the remaining cotton crops by 15%, likely due to increased resource use by larger wheat crops in the rotation.

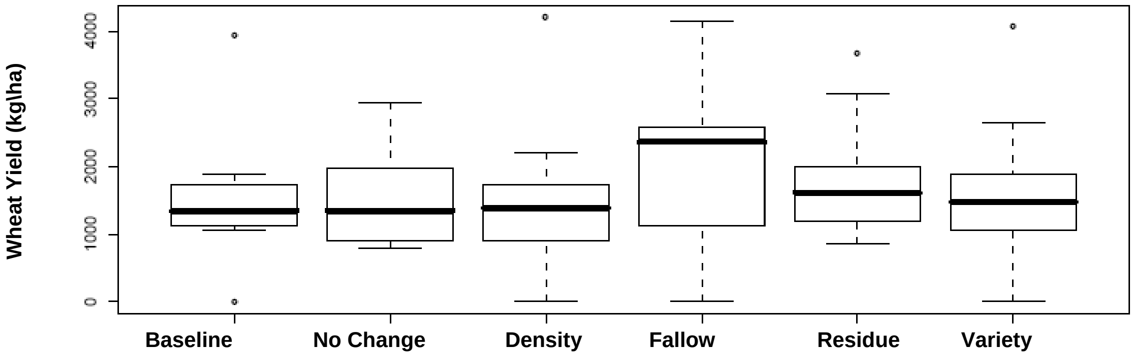


***Figure 24**: Jandowae – Simulated wheat yields (kg/ha) for Farm 3 (wheat and cotton production) under current climate conditions (baseline- 1957 to 2006) compared with simulated wheat yields under a 'mid' global warming scenario and resultant HADCM3.1 model projections for different management options*

Under the 'high' global warming scenario and HADCM3.1 projections greater warming and declines in rainfall reduced most yield benefits simulated in the 'mid' warming scenario. In this case whilst there is little change in median yields between the baseline and 'no change' case, median yield losses were simulated for the 'density' and 'variety' adaptation options (i.e. a 13% and 14% decline respectively – shift from 1348kg\ha to 1176kg\ha and 1168kg\ha) (Figure 25).

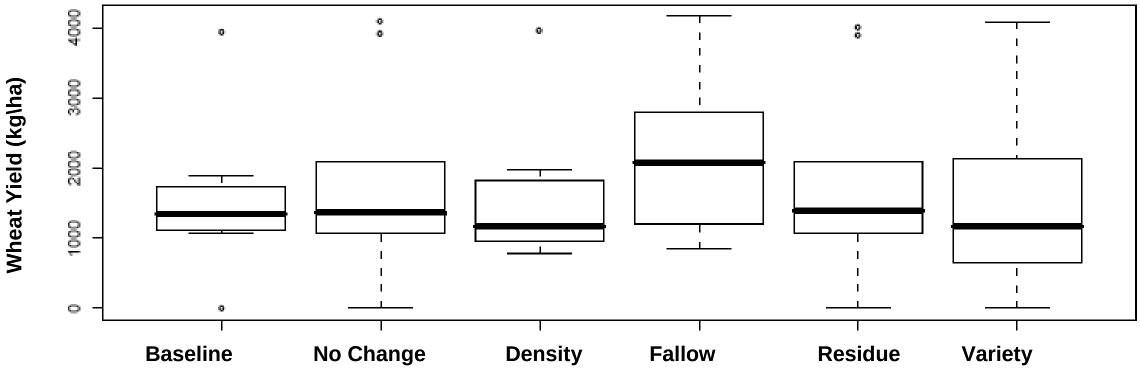


***Figure25**: Jandowae – Simulated wheat yields (kg/ha) for Farm 3 (wheat and cotton production) under current climate conditions (baseline- 1957 to 2006) compared with simulated wheat yields under a 'high' global warming scenario and resultant HADCM3.1 model projections for different management options*

Birchip Region – 2030

Under the 'mid' range global warming scenario (i.e. A2 SRES emission scenario) local Birchip seasonal temperatures are projected to increase by approximately 0.8 to 1.1°C and annual rainfall is projected to decline by 3 to 5% depending on climate model projections and farm location by 2030. These changes are measured relative to the 1990 historical temperature and rainfall baselines. As with the Jandowae analyses ambient CO_2 concentrations of approximately 451ppm were considered in the crop simulations associated with this 'mid' range global warming scenario. Under the 'high' range global warming scenario (i.e. A1T SRES emission scenario) local Birchip seasonal temperatures are projected to increase by approximately 1.2 to 1.4°C and annual rainfall is projected to decline by 5 to 8% depending on climate model projections and farm location by 2030. Ambient CO_2 concentrations in this scenario are approximately 440ppm, but the concentrations of other greenhouse gasses are higher than for the A2 scenario thus producing greater global warming.

In the case of Farm 1 (a wheat-pasture system) the mid-range 2030 climate change projections resulted in a 15% decline in median wheat yield if ‘no change’ in on-farm management occurred (i.e. a change from 3240kg/ha to 2715 kg/ha) (Figure 26). Reducing planting densities (i.e. ‘Density’) or choosing shorter season varieties (i.e. ‘Variety’) resulted in further declines in median yields compared with the ‘no change’ case (see Appendix A for more detail) (Figure 26). Introducing an additional pasture component in the rotation proved beneficial at this location as it served to offset yield losses associated with warmer and drier conditions. Resultant median yield were only reduced by 6% compared with baseline median yields.

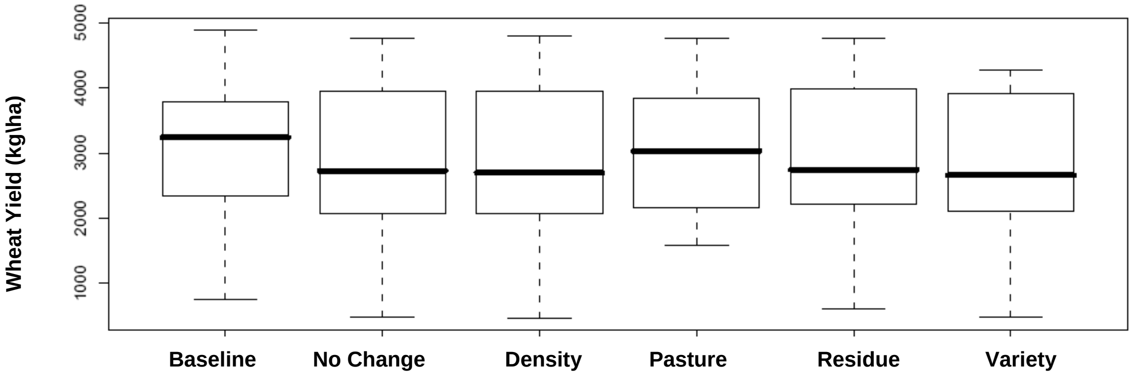


Figure 26*: Birchip – Simulated wheat yields (kg/ha) for Farm 1 (wheat/pasture) under current climate conditions (baseline- 1957 to 2006) compared with simulated wheat yields under ‘mid’ range global warming scenario and resultant HADCM3.1 model projections for different management options. These include no change in current management ‘No Change’, reduced planting density ‘Density’, increasing pasture ‘Pasture’, increasing residue retention ‘Residue’ and choosing shorter season varieties ‘Variety’. The lower and upper edges of the box represent the 25th and 75th percentile yield values, the black line represents the 50th percentile yield and the upper and lower whiskers represent the 10 and 90 percentile yield values.*

Significant improvements in the lowest yields were also attained through this adaptation option with the lowest simulated wheat yields rising from 754kg/ha in the baseline simulation to 1550kg/ha (Figure 26). Increasing the proportion of residue retained after harvest also served to improve median wheat yields compared to the ‘no change’ simulation, however median yields were still 14% lower than the simulated baseline yields. In all cases wheat yield variability increased in response to warmer and drier future climate conditions.

The yields simulated using projections from the MARK3 model (less warming and rainfall decline) resulted in only a 10% decline in median wheat yield if ‘no change’ in on-farm management occurred (i.e. a change from 3240kg/ha to 2900 kg/ha) (see Appendix B, Figure 4). Under these projected climate conditions all adaptation options examined, except the ‘Density’ option, provided improvements of between 2 to 4% in median yield compared with the ‘no change’ case. The increased pasture adaptation again provided most effective resulting in median yield losses of only 4% versus the 10% losses under ‘no change’ case (see Appendix B, Figure 4).

Under the 'high' global warming scenario (i.e. A1T SRES emission scenario) and HADCM3.1 model projections, median wheat yields in this farming system declined by approximately 24% (Figure 27). As in the 'mid' range warming scenario both increased pasture and residue management served to offset yield losses by 13 and 5% respectively.

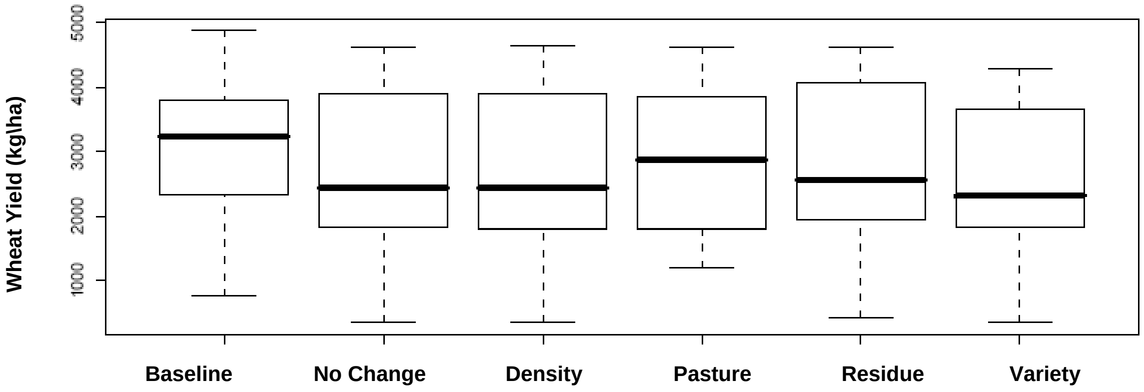


***Figure 27**: Birchip – Simulated wheat yields (kg/ha) for Farm 1 (wheat/pasture) under current climate conditions (baseline- 1957 to 2006) compared with simulated wheat yields under 'high' range global warming scenario and resultant HADCM3.1 model projections for different management options.*

Again wheat yield impacts from the MARK3 model projections resulting from the 'high' global warming scenario are slightly lower than those from the HADCM3.1 model (see Appendix B, Figure 5). Under these climate conditions all the adaptation options examined (except for the 'Density' adaptation) showed improved median yields of between 3 and 11% compared with the 'no change' case. Increasing the pasture component in the rotation again proved most effective at mitigating the impacts of warmer and drier conditions i.e. yield losses compared to the 'baseline' of 11% versus 18% in the 'no change' case' (see Appendix B, Figure 5).

In the case of Farm 2 (a mixed cropping and grazing system) the regional climate change projections generated by the HADCM3.1 climate model in response to a 'mid' range global warming scenario resulted in an 12% decline in median wheat yield if 'no change' was made to current management (i.e. from 3130kg/ha to 2770kg/ha) (Figure 28). By increasing residue retention (in an effort to reduce soil evaporation) simulated median yield losses were offset to only 6% lower than present. Increasing the amount of residue retained served to enhance yield performance in poorer years with the 25th percentile simulated yields 50% higher than present (i.e. 1780kg/ha versus 1160kg/ha) (Figure 28). In this farming system the farmer opted to examine the value of introducing two fallows in his rotation, both prior to growing wheat. In this instance the inclusion of the additional fallows served to increase median wheat yield by 3% above the current baseline yields. Similarly the 25th percentile simulated yields were also much higher than the baseline yields (Figure 28).

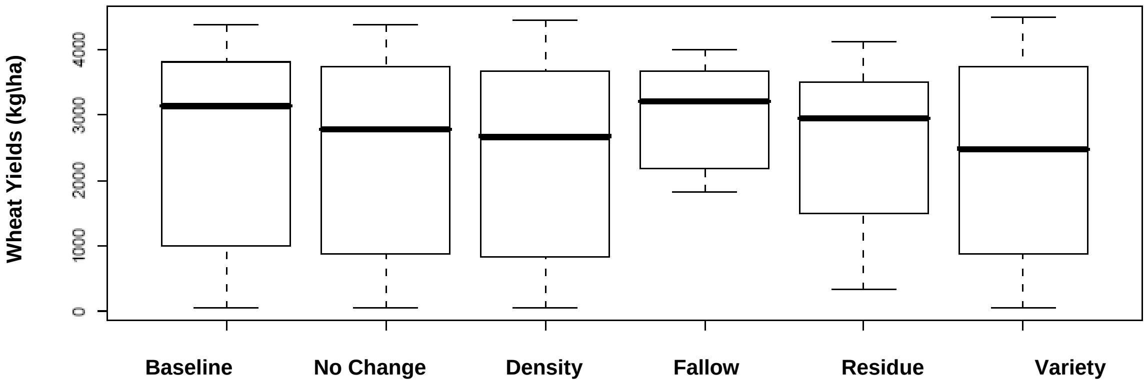


__Figure 28__: Birchip – Simulated wheat yields (kg/ha) for Farm 2 (mixed cropping/grazing) under current climate conditions (baseline- 1957 to 2006) compared with simulated wheat yields under 'mid' range global warming scenario and resultant HADCM3.1 model projections for different management options.

The yields simulated using the more modest projected changes from the MARK3 model resulted in similar impacts on wheat yields. In this case, only a 10% decline in median wheat yield occurred under the 'no change' in on-farm management simulations (i.e. a change from 3130kg/ha to 2780kg/ha) (Figure 29). Under these climate change conditions the 'Fallow' adaptation option enhanced the median yields by 7% compared to the baseline and a 17% improvement on the 'no change' case. The increased fallow adaptation also served to reduce the production variability by improving yields in the 1 to 25th percentile range (Figure 29).

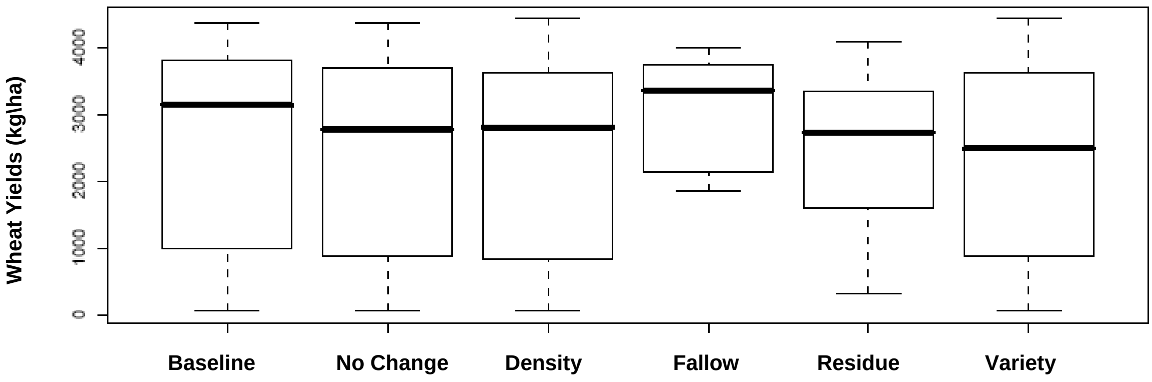


__Figure 29__: Birchip – Simulated wheat yields (kg/ha) for Farm 2 (mixed cropping/grazing) under current climate conditions (baseline- 1957 to 2006) compared with simulated wheat yields under 'mid' range global warming scenario and resultant MARK3 model projections for different management options.

The regional climate change projections generated by the HADCM3.1 climate model in response to the 'high' global warming scenario, when implemented for Farm 2 simulations, result in a median wheat yield decline of 20% for the 'no change' case. Under this degree of climate change the 'Fallow' adaptation option no longer simulates a median yield in excess of the baseline but a median yield 5% lower as opposed to 20% under 'no change' conditions. Enhancing residue retention also served to offset yield losses to within 16% of the baseline median yields (see Appendix B, Figure 6).

Under the 'high' global warming scenario and MARK3 model climate projections, median wheat yields fell by 15% under the 'no change' conditions (see Appendix B, Figure 7).

In a mixed cropping system (i.e. Farm 3), the 'high' global warming scenario (i.e. A1T SRES emissions scenario) and HADCM3.1 projected climate change resulted in 18% declines in simulated median yields if 'no change' in farm management occurred by 2030. In this mixed cropping system the introduction of a fallow greatly improved the median wheat yields with a 34% increase in median yields above present (i.e. 2160kg/ha to 2880kg/ha) (Figure 30). This large increase in simulated yields resulted from the placement of fallows preceded each wheat crop, allowing a significant accumulation of soil moisture prior to each wheat crop (see Appendix A explaining the nature of the adaptation options).

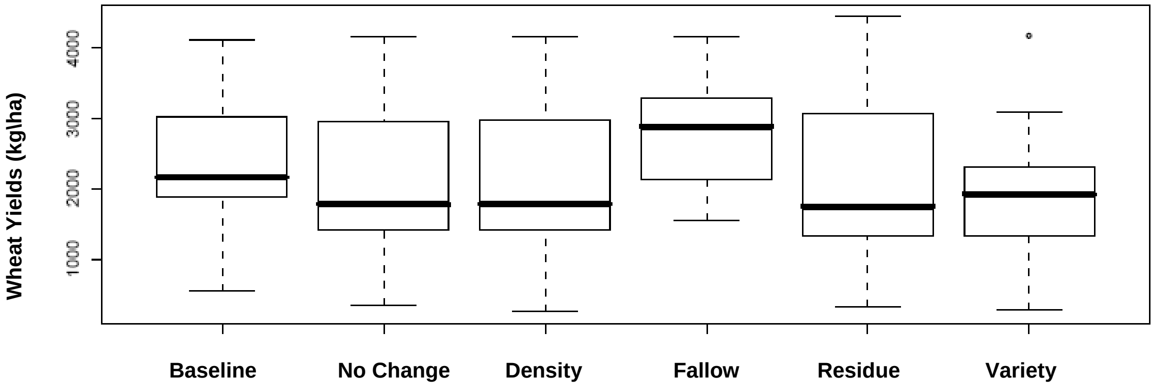


Figure 30: Birchip – Simulated wheat yields (kg/ha) for Farm 3 (mixed crop farming system) under current climate conditions (baseline- 1957 to 2006) compared with simulated wheat yields under a 'high' global warming scenario and resultant HADCM3.1 model projections for different management options.

Under the 'high' global warming scenario and MARK3 model climate change projections, simulated median wheat yields declined by approximately 15% (Figure 31). The 'Fallow' adaptation option still resulted in greater median yields (i.e. +20%) than for the 'baseline' simulation. The selection of a faster growing season wheat variety improved median yields by 6% compared to the median 'baseline' yield (i.e. 2030 kg/ha versus 2160kg/ha).

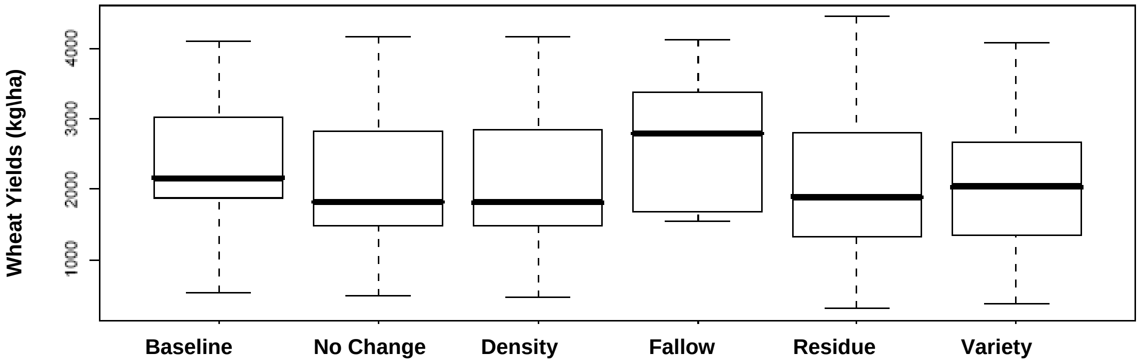


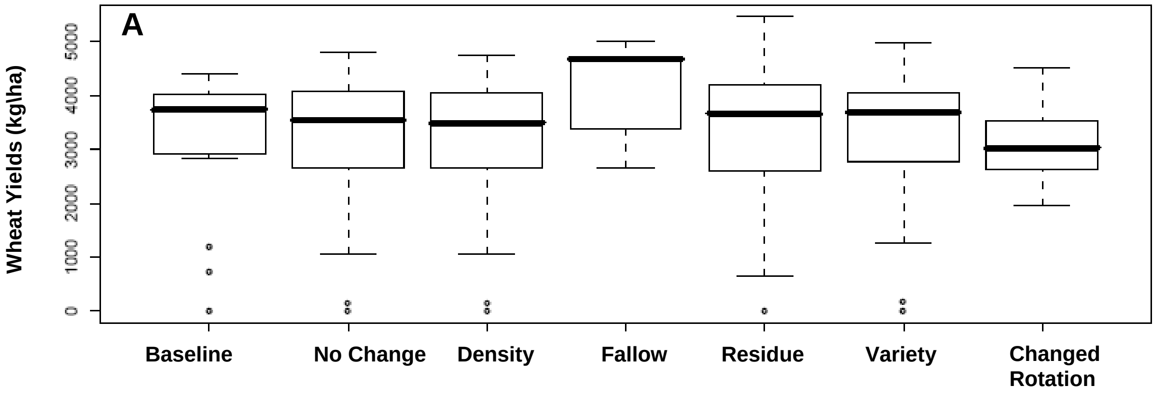
Figure 31: Birchip – Simulated wheat yields (kg/ha) for Farm 3 (mixed crop farming system) under current climate conditions (baseline- 1957 to 2006) compared with simulated wheat yields under a 'high' global warming scenario and resultant MARK3 model projections for different management options.

In a mixed cropping system to the northeast of Birchip (i.e. Farm 4), the ‘mid’ global warming scenario coupled with the HADCM3.1 and the MARK3 models resulted in only very small changes in the median yields if ‘no change’ to current management was made. In both cases a marginal 1% increase in the median yield was simulated (i.e. 3730kg/ha versus 3750kg/ha and 3770kg/ha respectively) driven primarily by higher CO_2 concentrations (see Appendix B, Figure 8 and 9). This would suggest that the current farming system is resilient to modest changes in rainfall and temperature projected at 2030 by both these models and emission scenarios.

Whilst the median yields increased under the ‘no change’ management scenario, yield variability was significantly increased (see Appendix B, Figure 8 and 9). In both cases the 25th percentile yields and lowest recorded yields were 2 to 5% lower than those in the ‘baseline’ simulation.

The ‘fallow’ adaptation option was implemented for this farming system by adding two fallow components into the seven year crop rotation (see Appendix A). Again this option provided significant increases in the median wheat yields compared with the ‘baseline’. In the case of the HADCM3.1 scenario, median yields increased by 26% (i.e. from 3730kg\ha to 4700kg\ha). For the MARK3 scenario median wheat yields increased by approximately 30% (i.e. up to 4830kg\ha). Under the more modest MARK3 warming and rainfall change, residue management also resulted in median yields approximately 1% higher then the ‘baseline’ yields. However, this was not the case for the HADCM3.1 scenario with median yield approximately 2% lower (see Appendix B, Figure 8 and 9). This clearly shows that the effectiveness of adaptation options is strongly dependent on the extent of rainfall and temperature change and how well suited the current cropping system is to the location.

Under the ‘high’ global warming scenario where temperatures are expected to warm by 1.2 to 1.4°C and rainfall is expected to decline by 5 to 8%, the ‘no change’ median yields declined by 5 and 4% for the HADCM3.1 and the MARK3 related simulations respectively (Figure 32a and 32b). ‘Fallow’, ‘residue’ and ‘variety’ adaptation options all served to offset yield losses. For the ‘fallow’ adaptation, median yields were 25% and 26% higher than the ‘baseline’ yields for the HADCM3.1 and the MARK3 simulations respectively (Figure 32a, b). For ‘residue’ and ‘variety’ adaptive management options yield losses were offset to within 2% of the ‘baseline’ median yields (Figure 32a, b).



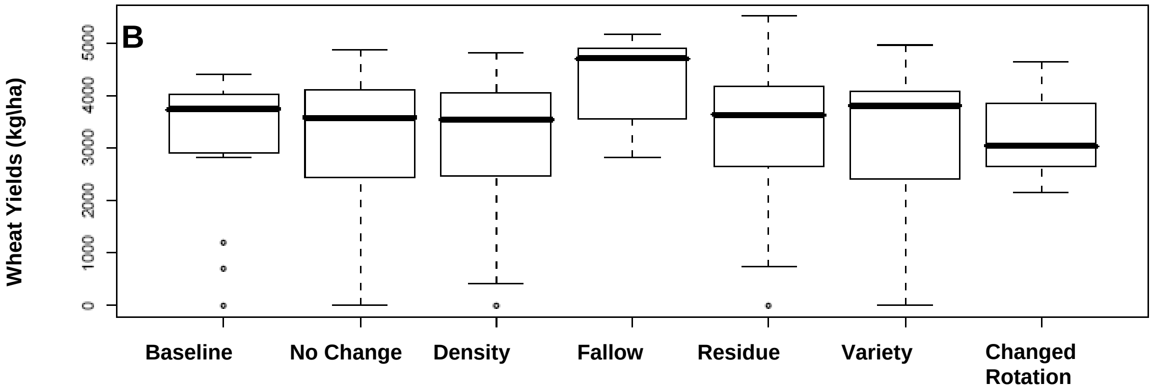


***Figure 32**: Birchip – Simulated wheat yields (kg/ha) for Farm 4 (a mixed cropping system) under current climate conditions ('baseline'- 1957 to 2006) compared with simulated wheat yields under 'high' global warming scenario and a) HADCM3.1 model projection and b) MARK3 model projection. Different adaptation options have been considered and the impact of these on the production of wheat assessed.*

For this farm, the farmer also requested we examine the impact of changing the crop rotation from a seven year rotation including fababeans, canola, wheat, and oats to one that dropped out the riskier crops such as canola and fababeans. The rotation change served to offset wheat performance in the lower yielding years (i.e. raised the 10th and 25th percentile yields).

The last farm analysed in the Birchip region (i.e. Farm 5), was characterised as a Wheat/Pasture farming system. Under the 'mid' global warming scenario and resultant HADCM3.1 climate change projections, median wheat yields increased by 13% if 'no change' in on-farm management occurred (i.e. a change from 1928 kg/ha to 2184 kg/ha) (Figure 33). Reducing planting densities (i.e. 'Density') or choosing shorter season varieties (i.e. 'variety') was shown to be neutral in offsetting yield losses, with median yield similar to the 'no change' case (Figure 33). Introducing an additional pasture component in the rotation proved beneficial as it served to further offset yield losses associated with warmer and drier conditions. Resultant median wheat yield was increased by 16% compared with the 'baseline' yields.

Significant improvements in the lowest yields (decreased risk) were also attained through this adaptation option with the 25th percentile simulated wheat yield rising from 1613kg/ha in the baseline simulation to 2099 kg/ha (Figure 33). The proportion of high-yielding crops also increased with the 75th percentile wheat yield of 3504 kg/ha some 30% higher than the 'baseline' 75th percentile yield of 2695 kg/ha. Increasing the proportion of residue retained after harvest also served to improve median wheat yields compared to the 'no change' simulation, and median yields were 19% higher than the simulated baseline yields.

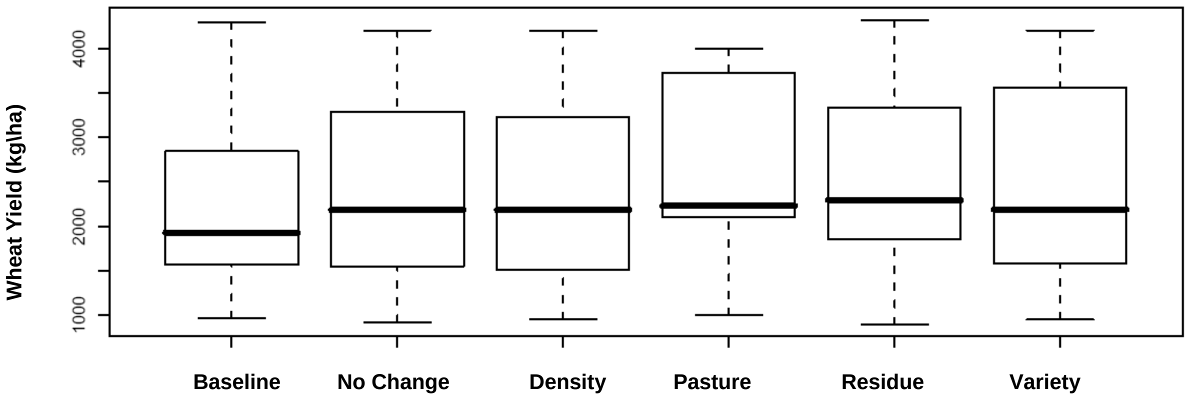


Figure 33: Birchip – Simulated wheat yields (kg/ha) for Farm 5 (wheat/pasture) under current climate conditions (baseline- 1957 to 2006) compared with simulated wheat yields under 'mid' range global warming scenario and resultant HADCM3.1 model projections for different management options. These include no change in current management 'No Change', reduced planting density 'Density', increasing pasture 'Pasture', increasing residue retention 'Residue' and choosing shorter season varieties 'Variety'. The lower and upper edges of the box represent the 25th and 75th percentile yield values, the black line represents the 50th percentile yield and the upper and lower whiskers represent the 10 and 90 percentile yield values.

Under the 'high' global warming scenario (i.e. A1T SRES emission scenario) and resultant HADCM3.1 climate change projections, median wheat yields on Farm 5 for the 'no change' increased by approximately 10% (Figure 34). Contrasting with the 'mid' range warming scenario however, both increased pasture and residue management were not found to increase the median wheat yields over the 'no change' scenario. They did reduce the likelihood of low-yielding crops however, with 25th percentile yields of 1676 and 1637 kg/ha respectively, compared with 1349 kg/ha for the 'no change' scenario.

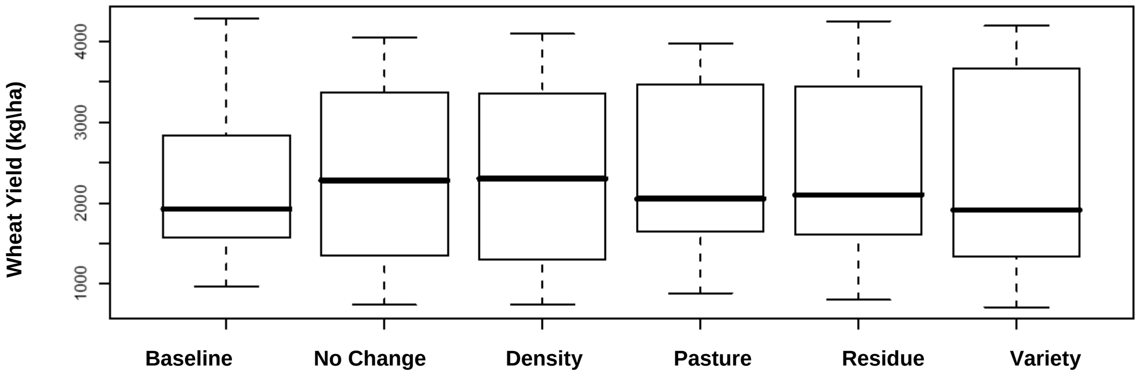


Figure 34: Birchip – Simulated wheat yields (kg/ha) for Farm 5 (wheat/pasture) under current climate conditions (baseline- 1957 to 2006) compared with simulated wheat yields under 'high' range global warming scenario and resultant HADCM3.1 model projections for different management options.

Mingenew Region – 2030

Under the 'mid' global warming scenario (i.e. A2 SRES emission scenario) local Mingenew seasonal temperatures are projected to increase by approximately 0.7 to 1.3°C and annual rainfall is projected to decline by 4 to 8% depending on climate model projections and farm location by 2030. These changes are measured relative to the 1990 historical temperature and rainfall baselines. Under the 'high' global warming scenario (i.e. A1T SRES emission scenario) local Mingenew seasonal temperatures are projected to increase by approximately 1.1 to 1.5°C and annual rainfall is projected to decline by 8 to 14%.

Dryland salinity poses significant challenges to current crop production in much of this case study region. Broad acre cereal crops and traditional pasture species grown in Australia do not tolerate salt and are seriously affected when salts concentrate within the root zone (LWA 2000). Total loss of crop and pasture production occurs where groundwater is close enough to the surface to discharge or concentrate salts; losses may be restricted to reduced yields where groundwater is deeper (LWA 2000).

Both climate models used to examine the likely impacts of climate change in this region suggest between 4 and 14% decline in annual rainfall. On farms where dryland salinity is prevalent (i.e. two case study farms), modest declines in rainfall could in reality serve to reduce both salinity risk and exposure. The APSIM model used in these analyses does not capture the benefits from reduction in soil salinity levels, hence this is a likely, but unaccounted, benefit to reduced rainfall in these relevant locations. Even so, the simulations below show that for some farms in the Mingenew Region, the advantages to production from a future increased atmospheric CO_2 concentration can outweigh the negative effects of moderate reductions in rainfall. The partitioning of negative and positive consequences in this instance was evidenced by a separate analysis conducted for Mingenew Farm 3, which examined the impacts on production using the future projected rainfall and temperature data, with and without associated CO_2 changes (see Figure 41 below).

In the case of Farm 1 (a mixed cropping/pasture system) the mid-range 2030 climate change projections from the HADCM3.1 model resulted in little measurable change in the median wheat yield for the 'no change' scenario (i.e. a change from 2330kg/ha to 2340kg/ha) (Figure 35). Under this scenario of modest temperature change and 5% less rainfall, simulated yield variability declined (i.e. difference between 25th and 75th percentile wheat yield was reduced). All the adaptation options examined for this farming system resulted in median yield benefits ranging from 1 (i.e. 'variety') to 29% (i.e. 'pasture') compared with the 'baseline' case (Figure 35). Whilst changing 'variety' only delivered a 1% increase in median yield significant improvements were simulated in the 25th percentile and highest yields (i.e. and 5 and 18% increases respectively).

Under the MARK3 'mid' climate change scenario, declines in annual rainfall of approximately 8% were simulated. Under this scenario, the reduction in rainfall served to increase the lowest yields by 18 to 40%, thus improving median yields for all adaptation options considered. Median yields however fell between 1% and 12% for both 'density' and 'residue' management options and increased by 12% for 'pasture' and 'variety options (see Appendix B, Figure 10).

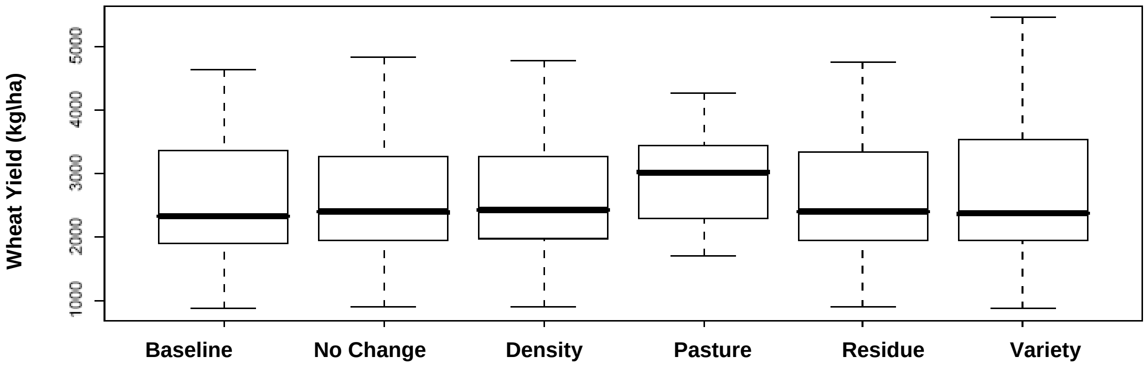


Figure 35: Mingenew – Simulated wheat yields (kg/ha) for Farm 1 (mixed cropping/pasture) under current climate conditions (baseline- 1957 to 2006) compared with simulated wheat yields under a 'mid' global warming scenario and resultant HADCM3.1 model projections for different management options.

Under the 'high' global warming scenario and MARK3 climate change projections, median wheat yields increased by 5% (i.e. baseline median yields of 2330kg\ha versus 2440kg\ha under 'no change') in response to increases in the lowest simulated yields. However as both the 25th and 75th percentile yields also declined mean yields fell by 4 to 12% for the 'density' and 'residue' management options respectively. As in the 'mid' warming scenario both increased pasture and changing variety served to increase yield losses by 24 and 5% respectively above baseline median yields (Figure 36).

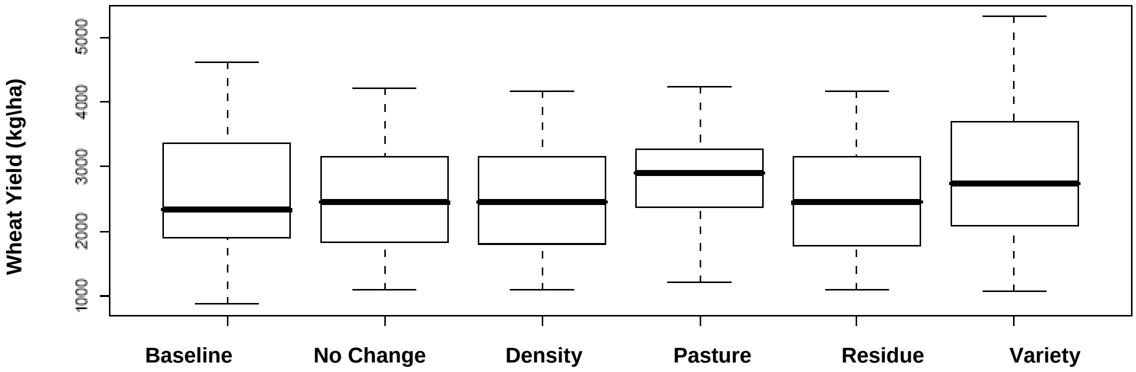


Figure 36: Mingenew – Simulated wheat yields (kg/ha) for Farm 1 (mixed cropping/pasture) under current climate conditions (baseline- 1957 to 2006) compared with simulated wheat yields under a 'high' global warming scenario and resultant MARK3 model projections for different management options.

Mingenew Farm 2 was characterised as a wheat/pasture farming system. A decline in median yields was simulated for all adaptation options including the 'no change' case in response to a 'mid' global warming scenario and resultant HADCM3.1 climate change projections (i.e. between 2 to 8% - reduction in baseline yields from 3150kg\ha to 2880kg\ha) (Figure 37).

Residue retention again did not prove to be a viable adaptation option with both median and 25th percentile yield values falling by 8% and 9% respectively (Figure 37)

Under the ‘mid’ warming scenario and 4% less rainfall, simulated yield variability declined across all adaptation options (i.e. difference between 25th and 75th percentile wheat yields declines). The option of choosing a shorter season variety proved most successful under these climate change conditions. Whilst no increase in median yield was simulated, increases in the 75th percentile yields were observed (i.e. an increase of 4% from 3400kg\ha to 3510kg\ha).

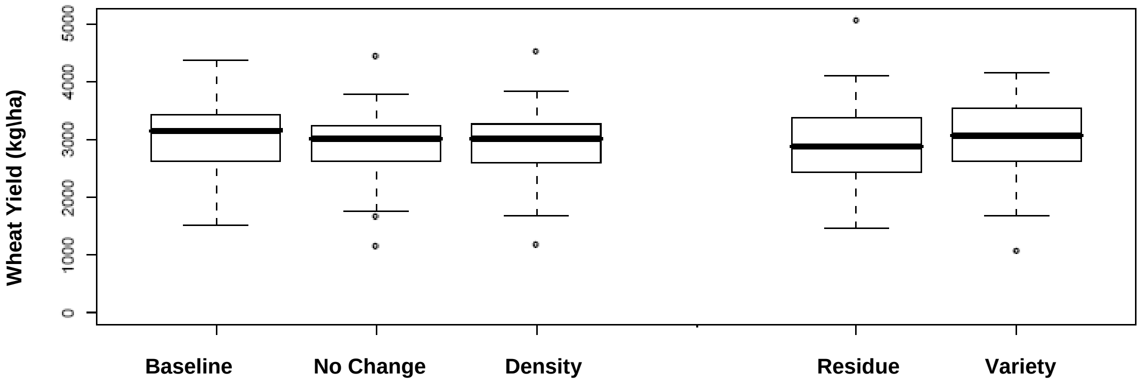


***Figure 37**: Mingenew – Simulated wheat yields (kg/ha) for Farm 2 (wheat/pasture) under current climate conditions (baseline- 1957 to 2006) compared with simulated wheat yields under a ‘mid’ global warming scenario and resultant HADCM3.1 model projections for different management options.*

Under the ‘high’ global warming scenario and resultant HADCM3.1 climate change projections, median wheat yields declined by 6% (i.e. ‘baseline’ median yields of 3150kg\ha versus 2970kg\ha under ‘no change’). As in the ‘mid’ global warming scenario, declines were simulated in median yields for all adaptation options (i.e. 5 to 10%) (Figure 38). The ‘variety’ option proved the most successful of the adaptations assessed with the 75th percentile yields 3.5% higher than the baseline yields (Figure 38).

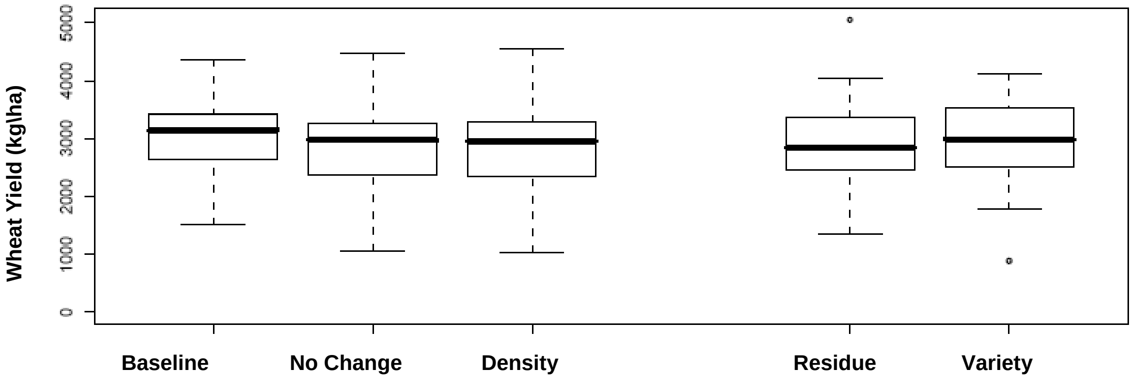


***Figure 38**: Mingenew – Simulated wheat yields (kg/ha) for Farm 2 (wheat/pasture) under current climate conditions (baseline- 1957 to 2006) compared with simulated wheat yields under a ‘high’ global warming scenario and resultant HADCM3.1 model projections for different management options*

Under a more extreme climate change scenario generated by the MARK3 model (i.e. temperature increase of 1.5°C and rainfall decline of 14%), a 17 to 19% decline in median wheat yields are simulated (Figure 39). Under these climate conditions the effectiveness of the ‘variety’ adaptation option was reduced, with only a 1%

difference between the 'no change' and 'variety' options (i.e. 2602kg\ha for the 'baseline' simulation versus 2630kg\ha) (Figure 39). Due to its location relative to other case study farms in this region (further inland), Farm 2 suffered greater projected reductions in rainfall (the distance from the coast precluded benefiting from locally-generated coastal rainfall) and these were not compensated for by the advantages of increased CO_2 concentrations. The soils are also notably poorer on this farm compared with the other four thus limiting any gains from the adaptation options implemented to conserve soil water storage (e.g. increased residue retention). This is covered further in the discussion section.

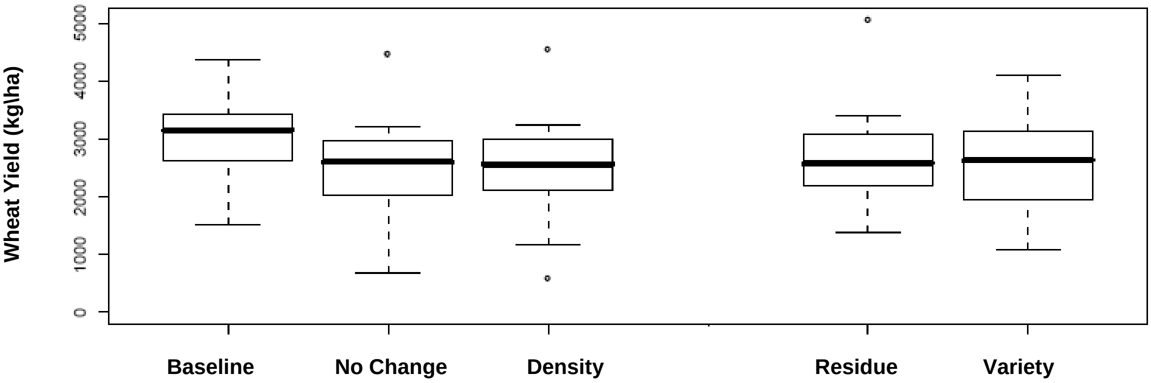


Figure 39: Mingenew – Simulated wheat yields (kg/ha) for Farm 2 (wheat/pasture) under current climate conditions (baseline- 1957 to 2006) compared with simulated wheat yields under a 'high' global warming scenario and resultant MARK3 model projections for different management options

The third case study farm for Mingenew, Farm 3, was classified as a mixed cropping system and located relatively near to the coast, with good quality, deep soils and higher baseline rainfall than the other four locations. As shown in Figure 40, for a 'mid' global warming scenario and resultant climate change projections from the HADCM3.1 GCM, the 'no change' management option presented positive impact on wheat yields. Maximum yields increased, minimum yields decreased, with an overall increase in median yield. The positive crop growth gains from projected atmospheric CO_2 increases overshadowed the negative impacts of reduced rainfall at this particular location. This is clearly illustrated in Figure 41. In this analysis the simulated baseline yields were compared against simulated future yields with and without CO_2. The impact of reducing seasonal rainfall by 8% and increasing temperatures by 1.3°C reduced mean wheat yields by approximately 5%. If the CO_2 effect was included then the mean future yields were approximately 8% higher than the mean baseline yields.

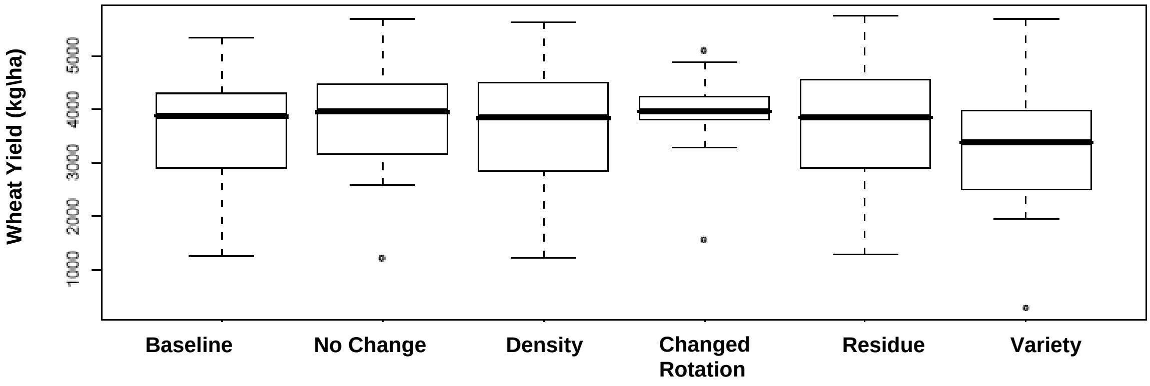


***Figure 40**: Mingenew – Simulated wheat yields (kg/ha) for Farm 3 (mixed cropping) under current climate conditions (baseline- 1957 to 2006) compared with simulated wheat yields under a 'mid' global warming scenario and resultant HADCM3.1 model projections for different management options*

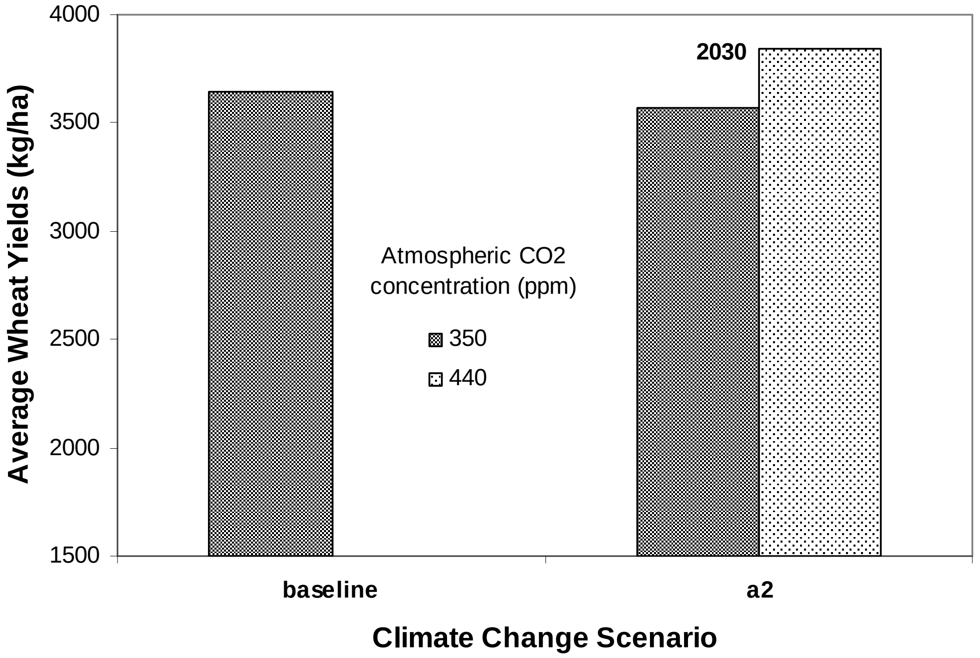


***Figure 41**: Mingenew – Simulated average wheat yields (kg/ha) for Farm 3(mixed cropping) under current climate conditions (baseline- 1957 to 2006) compared with simulated wheat yields under a 'mid' global warming scenario and resultant HADCM3.1 model projections for the 'no-change' option. Simulated results shown with (CO_2 = 440ppm) and without (CO_2 = 350ppm) projected CO_2 changes.*

There was little significant difference in median yields across all other adaptation options evaluated except for 'changed rotation'. For this option the crop rotation was shortened to include two wheat crops, three lupin crops and two oat crops (see Appendix A). The shortening of the crop rotation significantly reduced the wheat yield variability (Figure 40), by effectively increasing the pasture phase in the rotation, which in turn decreased the demand for water from the rotation as a whole, and hence increase the stored soil moisture available for the following wheat crop. Due to the good soils on this particular property this moisture was utilised, however reducing the occurrence of lupins (N-fixing legume) in the rotation reduced the available soil N, reducing the maximum possible wheat yields. On this farm the choice of shorter season cultivar (i.e. 'variety') resulted in significant reduction in median wheat yields (i.e. 12%) and for this reason was not an appropriate adaptation option in this instance (Figure 40).

Under the 'mid' global warming scenario and resultant MARK3 climate change projections, a similar pattern of yield response was simulated (see Appendix B, Figure 11). In this instance a 3% median yield increase was simulated for the 'changed rotation' adaptation option (se Appendix B, Figure 11).

Under the 'high' global warming scenario and resultant HADCM3.1 climate change projections, median wheat yields declined by between 1 and 16% compared with the 'baseline' simulations. In this instance all the adaptation options resulted in lower median yields than under the 'no change' management option (Figure 42). The 'variety' option proved least successful of all adaptation options, returning median yields 15% below the 'no change' management option (Figure 42). Under these climate change conditions the changed rotation still represented an appropriate option to consider as the lower yielding years (i.e. lowest 25 percent) were 22% higher than the 'baseline' and 10% higher than the 'no change' simulated yields (Figure 42).

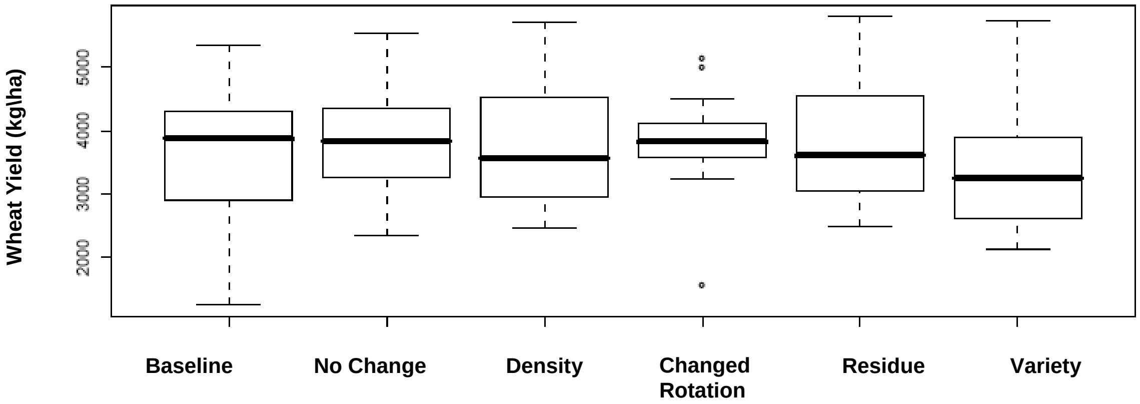


***Figure 42**: Mingenew – Simulated wheat yields (kg/ha) for Farm 3 (mixed cropping) under current climate conditions (baseline- 1957 to 2006) compared with simulated wheat yields under a 'high' global warming scenario and resultant HADCM3.1 model projections for different management options*

Under the 'high' global warming scenario and MARK3 model projections, median wheat yields declined by between 1 and 15% compared with the 'baseline' simulations. In this instance the changed rotation provided improved median yields compared with the 'no change' management option (see Appendix B, Figure 12).

The fourth case study farm in this region (i.e. Farm 4) was also classified as a mixed cropping system. This farm was located on loamy soils, which have higher water holding capacity than many of the soils in the vicinity. The farmer indicated an interest in exploring the value of fallowing on this soil type. We were directed to introduce two 'fallows' in the four year wheat, canola and fababean rotation, each falling prior to a wheat crop. The resultant impacts were favourable under both the A2 and A1T emission scenarios using the Mark3 model, with median yield 16% and 3% higher respectively, than the 'baseline' (Figure 43a,b). On the loamy earth soils the residue retention option provided the greatest median yield benefits with simulated yields 24% and 18% higher than baseline yields (Figure 43a,b).

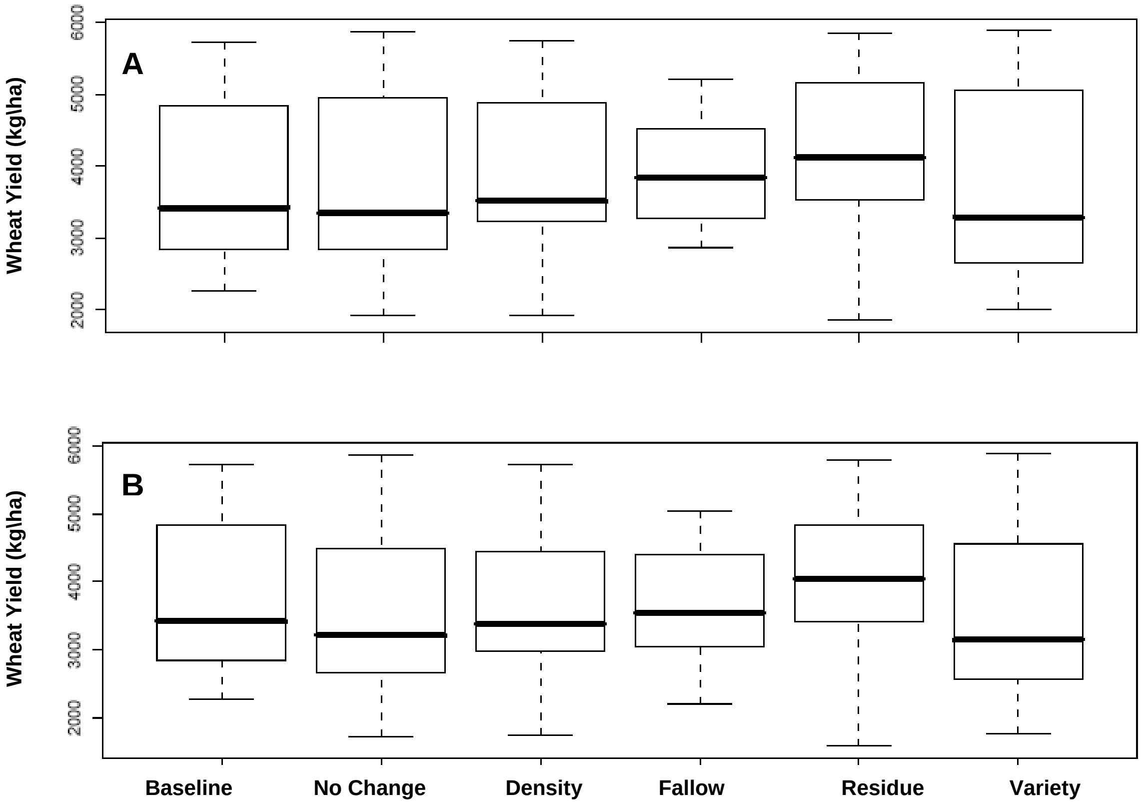


***Figure 43**: Mingenew – Simulated wheat yields (kg/ha) for Farm 4 (mixed cropping) under current climate conditions ('baseline'- 1957 to 2006) compared with simulated wheat yields under a) a 'mid' global warming scenario and MARK3 model projections and b) under a 'high' global warming scenario and MARK3 model projections. Different adaptation options have been considered and the impact of these on the production of wheat assessed. These adaptation options include no change in current management 'No Change', reduced planting density 'Density', increasing fallow 'Fallow', increasing residue retention 'Residue', and choosing shorter season varieties 'Variety'.*

On this farm the decreasing the planting density also served to offset potential yield losses. This would suggest that the current seeding rates may not be well suited for the current environmental conditions

2070 Projection Analyses

The 2070 scenarios generally resulted in more severe negative outcomes associated with the range of adaptive management options considered, in comparison with the 2030 scenarios. The degree of impact varied between farms, being a function of the degree of seasonal change in rainfall and temperature the case study region, position within the region, soil type and how well the current management was optimised to climatic conditions. The results of the analyses are shown below for the 'high' (A1T) emissions scenario only. Due to the longer timescale, and consequently higher degree of uncertainty, it was decided to concentrate on the A1T emission scenario as the upper limit of likely climate change and most severe test case for suggested adaptation options.

Jandowae Region – 2070

The HADCM3.1 GCM projected a drier climate for the Jandowae region, than the MARK3 model for the 2070 scenarios – opposite to the Australian west coast where the MARK3 model projected the drier future.

Farm 1, based predominantly on winter cropping, experienced more negative impacts on wheat yields from projected climatic change under the 2070 scenarios than under the 2030 scenarios. As can be seen in Figure 44, without changes to on-farm management average wheat yield reductions of between 1 and 11% were simulated, compared with increases under the 2030 projections. The adaptation option that proved most effective at offsetting the project climate changes in 2070 was the 'fallow' which resulted respectively in 15% and 3% increase in the median wheat yield compared with the 'no change' simulation results for both the HADCM3.1 and MARK3 projections respectively. This adaptation option served to increase the soil water available to the wheat crop, thereby counteracting the impact of projected rainfall reductions. The crop simulations initialised with the HADCM3.1 climate projections simulated increased chances of low yields (-8% for 25thpercentile), offset by increased chances of top-end yields (26% for 75th percentile), illustrating the increased variability of crop productions by 2070.

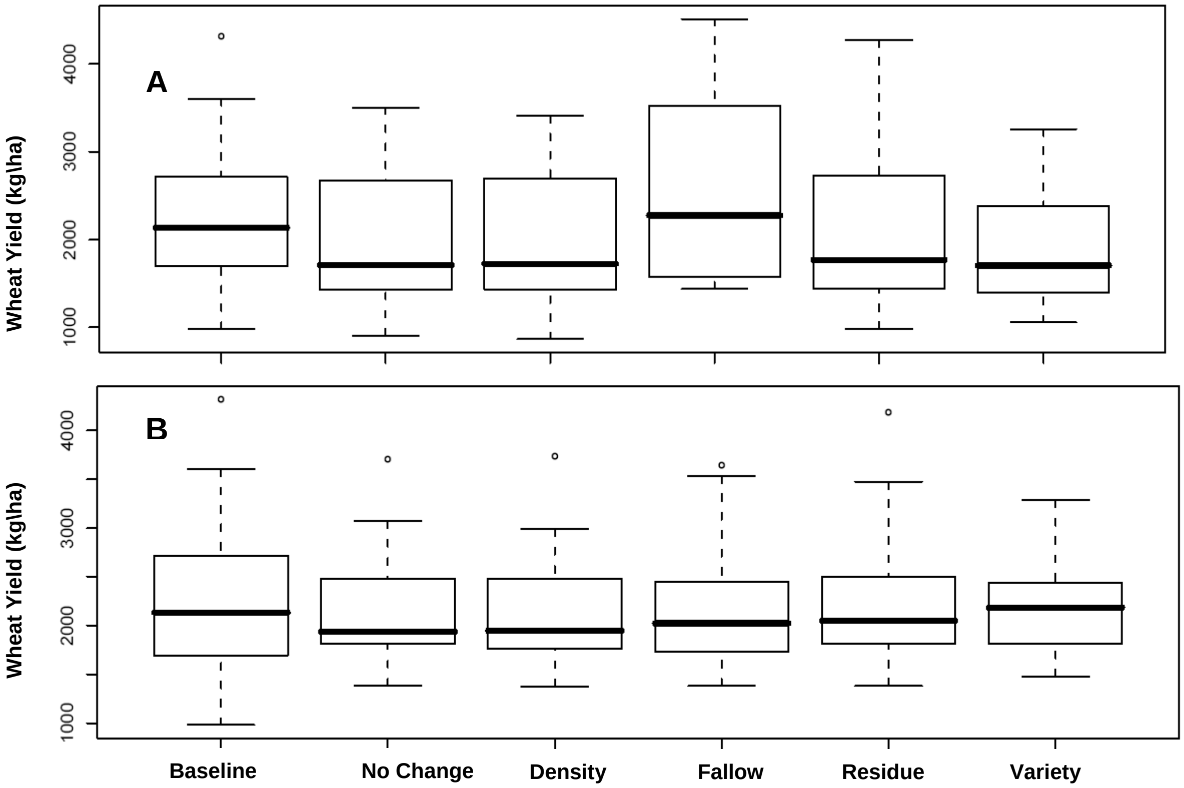


Figure 44: Jandowae Farm 1 adaptive strategy wheat yields for 2070 'high' scenario (A1T) as projected by a) HADCM3.1 and b) MARK3 GCM models – Simulated wheat yields (kg/ha) under current climate conditions ('baseline'- 1957 to 2006) compared with simulated wheat yields for a range of different adaptation options. These adaptation options include no change in current

management 'No Change', reduced planting density 'Density', increasing fallow 'Fallow', increasing residue retention 'Residue', and choosing shorter season varieties 'Variety'.

In the MARK3 climate change projections (i.e. smaller rainfall decline) the effect of introducing either a 'fallow' or a 'residue' adaptation strategy differed from results generated using the drier HADCM3.1 projections. In this instance both adaptation strategies resulted in a reduction in the number of low-yielding years (1% and 5% respective increases for the 25th percentile compared to the 'baseline'), and a concurrent reduction in the high-yielding crops (10% and 9% respective reductions for the 75th percentile compared to the 'baseline'). This suggests that under much drier conditions fallowing is an effective adaptation option at this location with enhanced residue retention less so. Under slightly less severe declines in projected rainfall enhanced residue retention provided slightly more beneficial than fallowing.

At Jandowae Farm 2 (Figure 45), sorghum represented the component of the crop rotation studied in these simulations. Implementing the HADCM3.1 climate projections resulted in notably decreased sorghum performance for all the adaptive options considered, apart from 'increased residue' which was simulated to effectively offset change rainfall and temperature impacts. However this farm relies on crop residues for income from animal grazing, hence this adaptive option is likely to have negative whole farm implications in terms of grazing material, even though it serves to maintain sorghum yield through enhanced soil water retention.

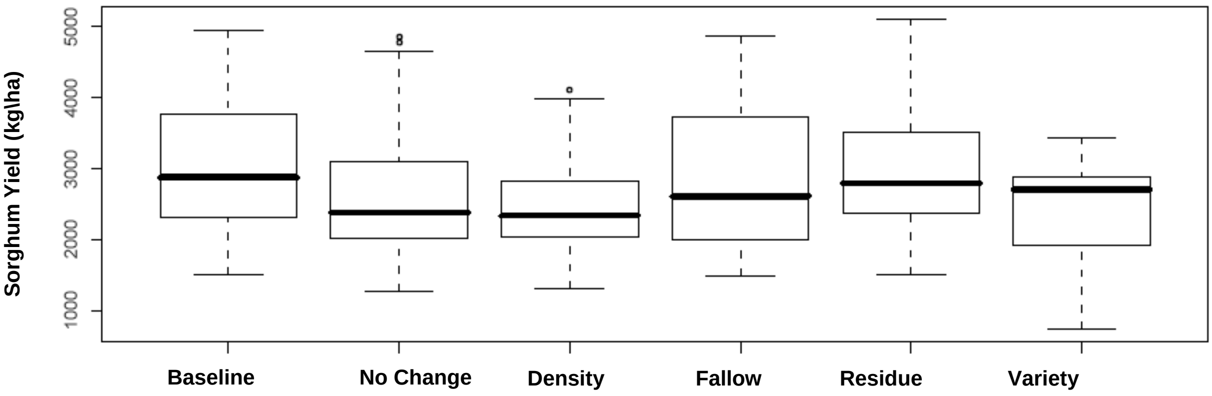


***Figure 45**: Jandowae Farm 2 adaptive strategy sorghum yields for 2070 'high' scenario (A1T) as simulated by the APSIM crop model initialised by the HADCM3.1 climate projections. Simulated sorghum yields (kg/ha) under current climate conditions ('baseline'- 1957 to 2006) compared with simulated sorghum yields for a range of different adaptation options. These adaptation options include no change in current management 'No Change', reduced planting density 'Density', increasing fallow 'Fallow', increasing residue retention 'Residue', and choosing shorter season varieties 'Variety'.*

Jandowae Farm 3 (Figure 46a,b), a wheat and cotton farming system (occasional chickpea), experienced gains in projected wheat yields under the less severe MARK3 climate change projections, except under the 'quicker crops' (i.e. altered variety) option. Gains were less forthcoming under the more severe projected climate change conditions generated from the HADCM3.1 projections. Particularly notable however, was the greatly increased wheat yield variability in the 'no change' management scenario for both of the GCM projections, compared with the 'baseline' simulation, indicating greatly increased risk associated with individual wheat crops with climate change under current management. The 75th and 25th percentile crops went from a ‘baseline’ of 1659 kg/ha and 1154 kg/ha respectively, to 568 and 2265 kg/ha under the more severe climate conditions projected by the HADCM3.1 model, as opposed to 1075 and 2178 kg/ha generated by use of the less severe MARK3 climate change projections (Figure 46a,b). The ‘increased fallow’ management option had a particularly positive effect on wheat yields under the HADCM3.1 projection, but less value under MARK3. This was due to the greater importance of soil water conservation under the drier 2070 projections.

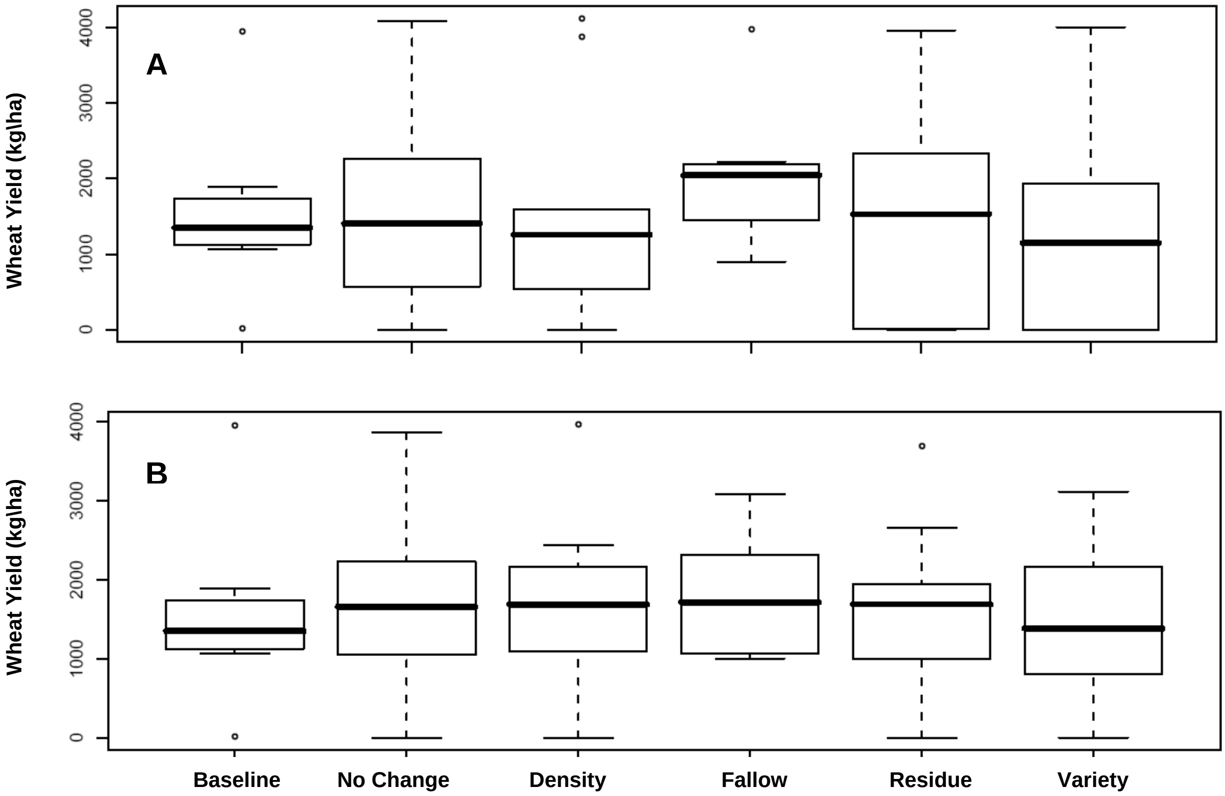


***Figure 46**: Jandowae Farm 3 adaptive strategy wheat yields for 2070 ‘high’ scenario (A1T) as projected by a) HADCM3.1 and b) MARK3 GCM models – Simulated wheat yields (kg/ha) under current climate conditions (‘baseline’ - 1957 to 2006) compared with simulated wheat yields for a range of different adaptation options. These adaptation options include no change in current management ‘No Change’, reduced planting density ‘Density’, increasing fallow ‘Fallow’, increasing residue retention ‘Residue’, and choosing shorter season varieties ‘Variety’.*

Birchip Region – 2070

The HADCM3.1 GCM once again projected a drier 2070 climate for the Birchip region, than the MARK3 model – although with slightly less separation in rainfall change than in the Jandowae region. For example, for Farm 1 the historical annual rainfall of 359mm was projected to decrease to 297mm under the HADCM3.1 projections, and 319mm under the MARK3 projections.

In the case of Farm 1 (a wheat-pasture system) the A1T 2070 climate change projections from the HADCM3.1 GCM resulted in a 26% decline in median wheat yield if ‘no change’ in on-farm management occurred (i.e. a change from 3240kg/ha to 2397 kg/ha) (Figure 47a). Reducing planting densities (i.e. ‘Density’) or choosing shorter season varieties (i.e. 'Variety') had a neutral effect on wheat yield performance compared with the 'no change' case. Introducing an additional pasture component in the rotation proved beneficial at this location as it served to offset yield losses associated with warmer and drier conditions. Resultant median yield increased by 4% compared with 'baseline' median yields, however the overall average wheat yield fell by 6%, from 3240 kg/ha to 2870 kg/ha.

The yields simulated using projections from the MARK3 model (reduced warming and rainfall decline) resulted in a 19% decline in median wheat yield if 'no change' in on-farm management occurred (i.e. a change from 3240kg/ha to 2624 kg/ha) (Figure 47b). Under this climate change scenario, the 'pasture' and 'residue' adaptation options provided improvements on the 'no change' median yield of 14 and 7 % respectively. This is not surprising given their direct impact on subsoil water availability for the wheat crop, and considering that the mean annual rainfall at this location was projected to drop to 319mm, making it an even more marginal water environment for cropping.

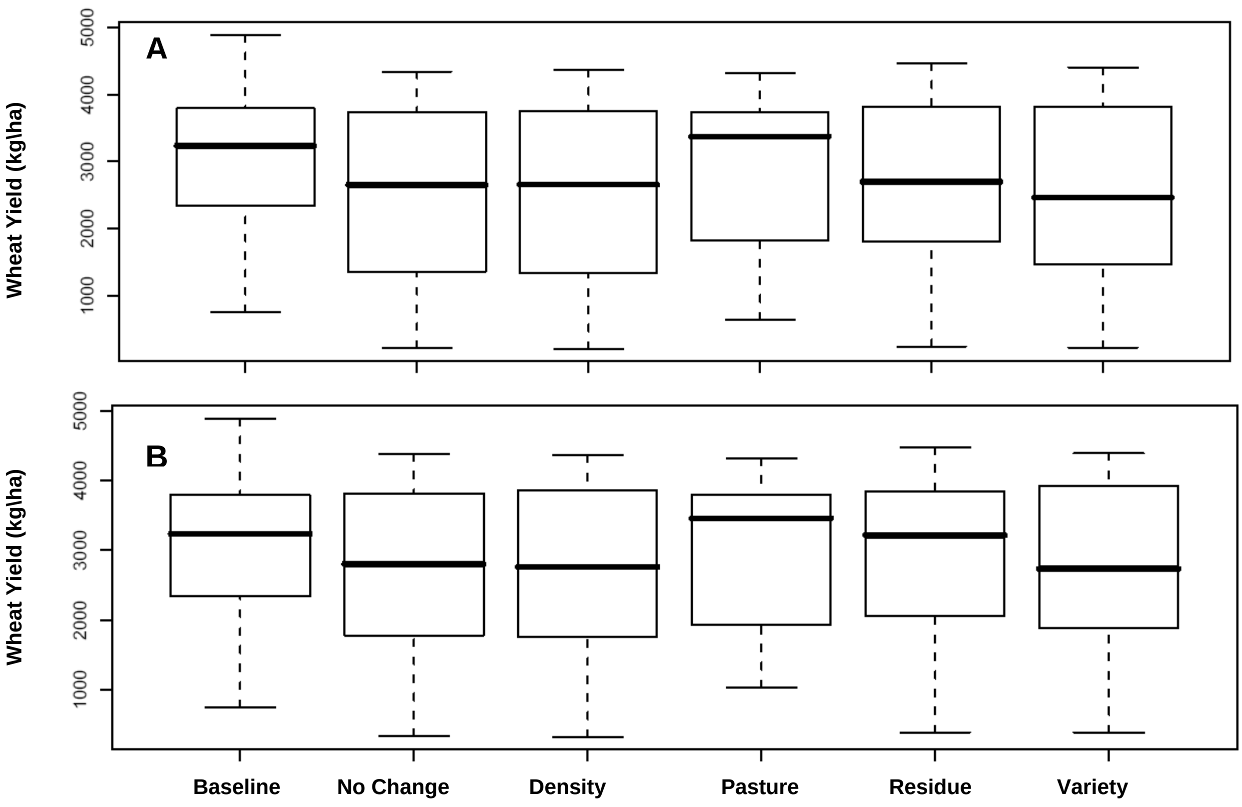


***Figure 47**: Birchip Farm 1 adaptive strategy wheat yields for 2070 'high' scenario (A1T) as projected by a) HADCM3.1 and b) MARK3 GCM models – Simulated wheat yields (kg/ha) under current climate conditions ('baseline'- 1957 to 2006) compared with simulated wheat yields for a range of different adaptation options. These adaptation options include no change in current management 'No Change', reduced planting density 'Density', increasing pasture 'Pasture', increasing residue retention 'Residue', and choosing shorter season varieties 'Variety'.*

Birchip Farm 2, a mixed cropping/grazing enterprise, was simulated to respond in similar fashion to the projections of both the HADCM3.1 and MARK3 climate change projections. Significant reductions in average wheat yield due to projected climate change from the 'no change' option were simulated, compared with the ‘baseline’ yields. These represented a decrease of 23% (3130 kg/ha down to 2378 kg/ha) for the HADCM3.1 projection and a decrease of 20% from the MARK3 model (down to 2504 kg/ha) (Figure 48a,b). Most of the adaptation options examined were unable to bring wheat yields back up to ‘baseline’ levels or make any improvements on the ‘no change’ option, other than increasing the ‘fallow’ proportion in the rotation which served to increase the overall average wheat yield over the ‘baseline’ by 2378 kg/ha up to 2756 kg/ha (for the HADCM3.1 model, similar with MARK3), with a corresponding reduction in the number of low-yielding crops, and an increase in the number of high-yielding crops (Figure 48a,b). As can be seen in Appendix A, this adaptation option was achieved by inserting two fallow periods into the rotation to enhance stored soil moisture levels for subsequent crops. Each of the fallows was inserted before a wheat crop, so this positive response is not unexpected. However because a fallow period does not earn the farmer any money directly, a pertinent question is whether the inclusion of two non-profit years in ten (as per Appendix A) is a truly cost-effective measure when the productivity of the whole paddock is considered over the long term.

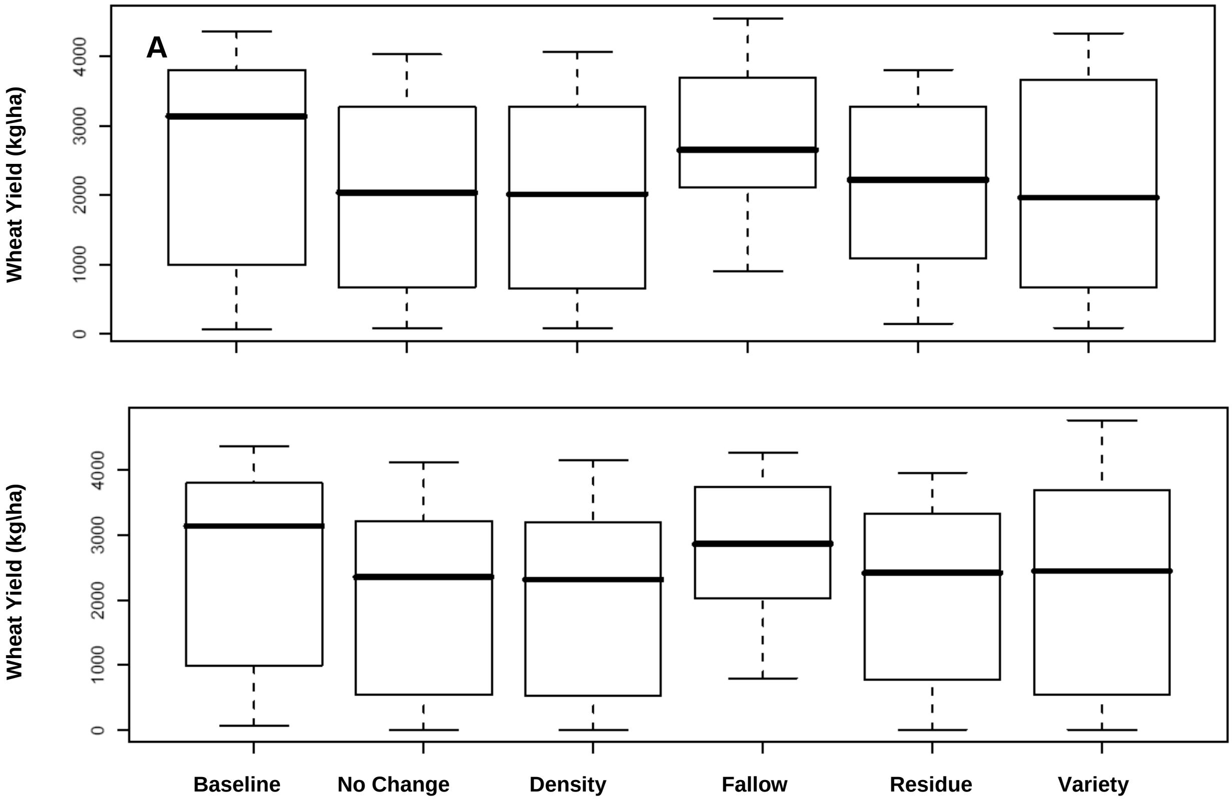


Figure 48: Birchip Farm 2 adaptive strategy wheat yields for 2070 ‘high’ scenario (A1T) as projected by a) HADCM3.1 and b) MARK3 GCM models – Simulated wheat yields (kg/ha) under current climate conditions (‘baseline’- 1957 to 2006) compared with simulated wheat yields for a range of different adaptation options. These adaptation options include no change in current management ‘No Change’, reduced planting density ‘Density’, increasing fallow ‘Fallow’, increasing residue retention ‘Residue’, and choosing shorter season varieties ‘Variety’.

Birchip Farm 3, a mixed cropping system, showed similar simulated impacts on production as Farm 2. The average yield reductions comparing the ‘baseline’ scenario to that generated by not adapting to projected climate change ('no change' scenario) were 21 and 19% respectively for the HADCM2 and MARK3 GCM projections. This corresponded to a drop from the baseline average wheat yield of 2160 kg/ha, down to 1706 and 1749 kg/ha for the two GCM projections respectively (Figure 49a,b). As in Farm 2, the increased 'fallow' adaptation option looks a highly viable alternative for wheat yields in this paddock, but the same question remains as to overall cost-effectiveness of this adaption option. See subsequent section "Overall Gross Margins". The simulations of the increased pasture option resulted in average wheat yields of 2710 kg/ha and 2867 kg/ha for the HADCM3.1 and MARK3 GCM projections respectively, representing enhancements over the 'baseline' yield of 2160 kg/ha (Figure 49a,b). This adaptation option also provided greatly enhanced reductions in yield variability, or risk, with 25th and 75th percentile yields of 2482 kg/ha and 3150 kg/ha (for the HADCM3.1 GCM), compared with the baseline figures of 1902 kg/ha and 2893 kg/ha, and the 'no change' figures of 1252 kg/ha and 2750 kg/ha.

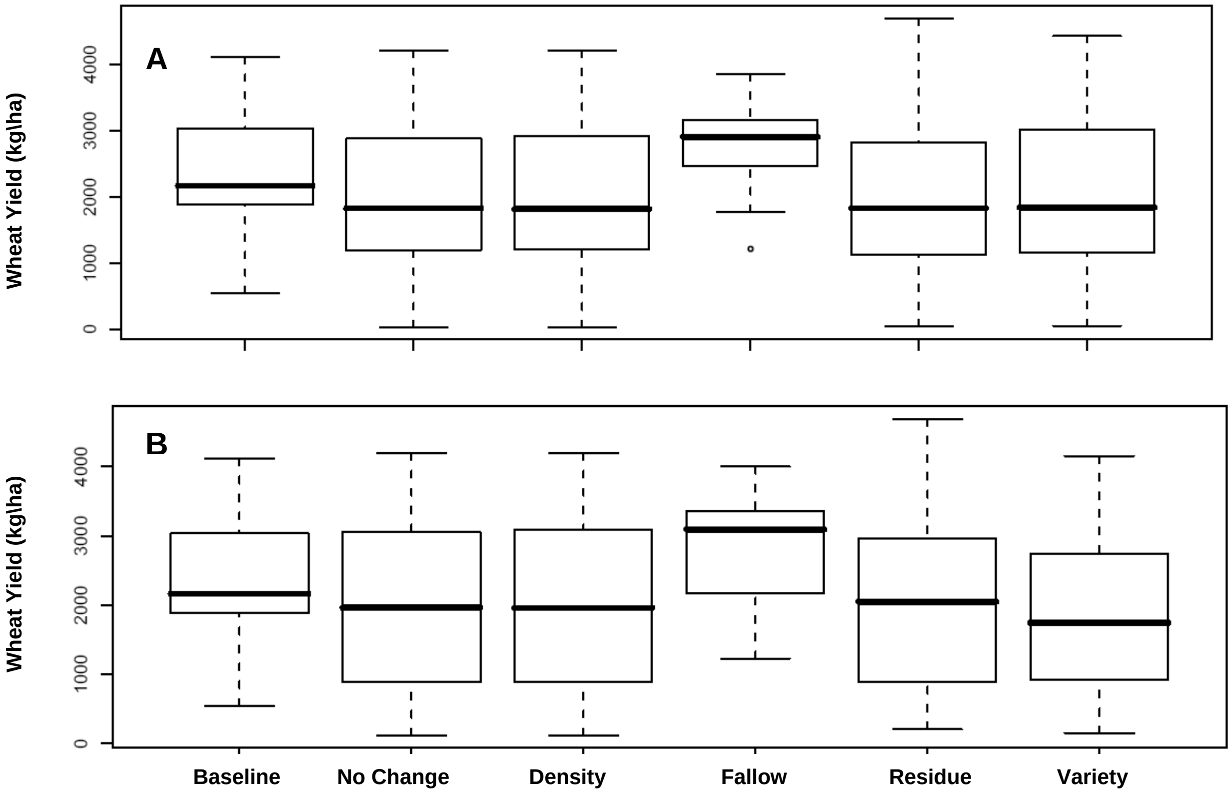


Figure 49: Birchip Farm 3 adaptive strategy wheat yields for 2070 'high' scenario (A1T) as projected by a) HADCM3.1 and b) MARK3 GCM models – Simulated wheat yields (kg/ha) under current climate conditions ('baseline'- 1957 to 2006) compared with simulated wheat yields for a range of different adaptation options. These adaptation options include no change in current management 'No Change', reduced planting density 'Density', increasing pasture 'Pasture', increasing residue retention 'Residue', and choosing shorter season varieties 'Variety'.

Birchip Farm 4, also classified as a mixed cropping system, showed similar value from the increased fallow period as did Farms 2 and 3. Once again the result raised average yields and reduced risk (see Figure 50a,b). In this farm also, the 'increased residue' and 'quicker variety' options provided potentially viable adaptation options in comparison with the 'no change' scenario, however neither was able to recoup the yield reductions due to projected climate change from each of the GCMs. The 'increased residue' option resulted in a greater likelihood of high-yielding crops in comparison with the 'no change' with little effect on low-yielding crops. This farm also experimented with an additional option "changed rotation", which saw fababeans drop out of the previous fababean-wheat-canola-oats rotation. This did not result in any average wheat yield gains, however the simulations indicated that a reduction in the number of low-yielding wheat crops would be possible.

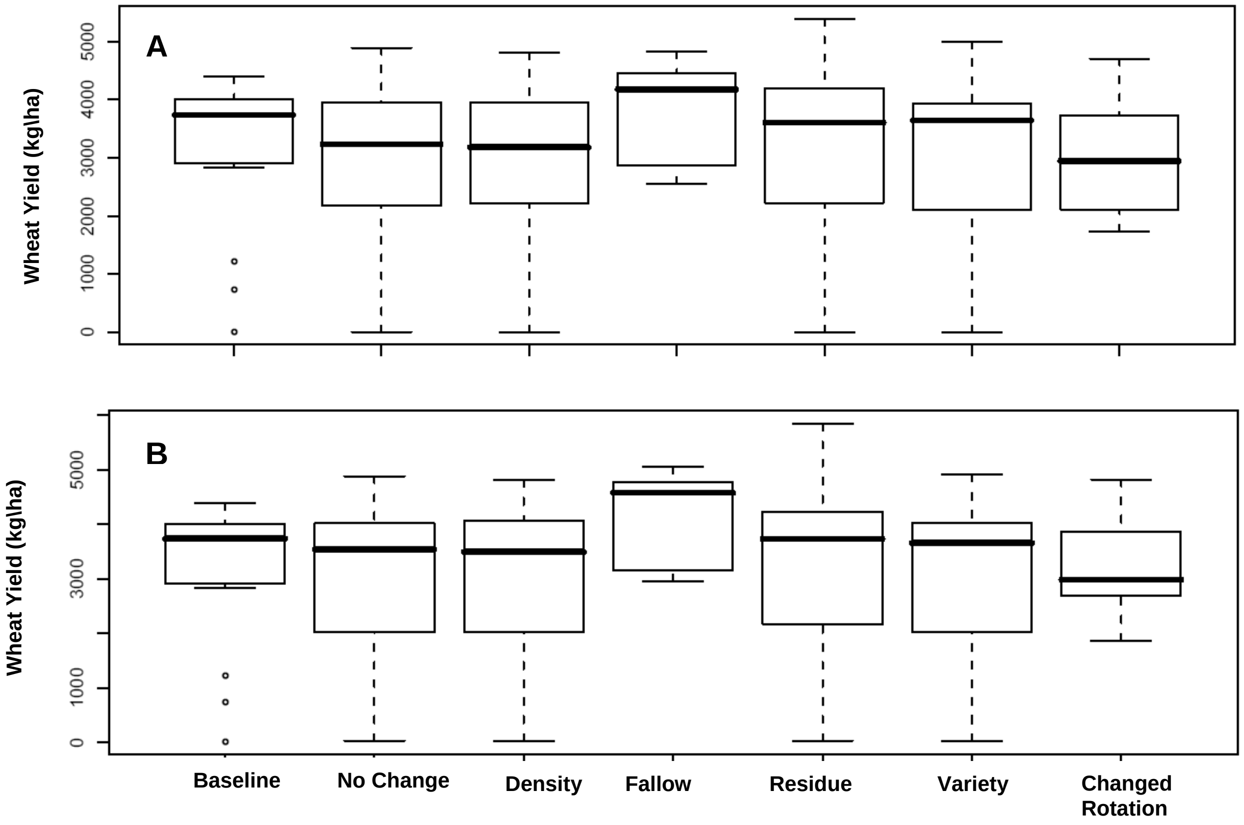


***Figure 50**: Birchip Farm 4 adaptive strategy wheat yields for 2070 'high' scenario (A1T) as projected by a) HADCM3.1 and b) MARK3 GCM models – Simulated wheat yields (kg/ha) under current climate conditions ('baseline'- 1957 to 2006) compared with simulated wheat yields for a range of different adaptation options. These adaptation options include no change in current management 'No Change', reduced planting density 'Density', increasing fallow 'Fallow', increasing residue retention 'Residue', and choosing shorter season varieties 'Variety', and changed rotation 'Changed Rotation'..*

Birchip Farm 5, a wheat-pasture system, provided a general contrast with other Birchip region farms by exhibiting a simulated increase in median wheat yields under climate change projections from both GCMs. This did not translate to increased average yields, except in the case of the adaptive option 'retain residue' where a small increase in average wheat yields (2%) was simulated over the 'baseline' (Figure 51). For all the other adaptive options, a small decrease in average yields was simulated, accompanied by increased risk and chance of achieving low-yielding crops.

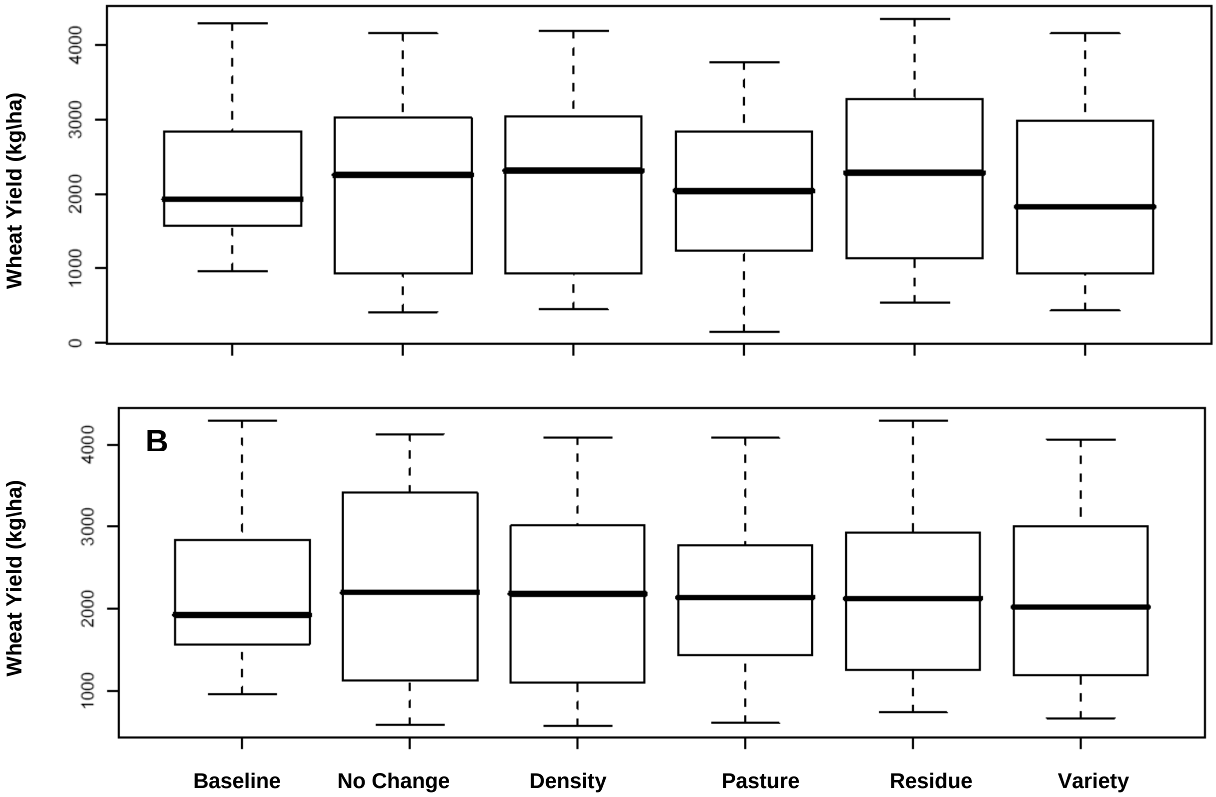


Figure 51*: Birchip Farm 5 adaptive strategy wheat yields for 2070 'high' scenario (A1T) as projected by a) HADCM3.1 and b) MARK3 GCM models – Simulated wheat yields (kg/ha) under current climate conditions ('baseline'- 1957 to 2006) compared with simulated wheat yields for a range of different adaptation options. These adaptation options include no change in current management 'No Change', reduced planting density 'Density', increasing pasture 'Pasture', increasing residue retention 'Residue', and choosing shorter season varieties 'Variety'.*

Mingenew Region – 2070

The results for the 2070 simulations in the Mingenew district highlighted the significant impacts distance from the coast and quality of soil have in avoiding negative climate change impacts under the projections from both HADCM3.1 and MARK3 GCMs for 2070. The MARK3 model projected dryer conditions by 2070 for this area than the HADCM3.1 model, however farms nearer the coast with better soils were able to buffer these changes to a much greater extent than the single farm (Farm 2) located on the far inland edge of the cropping region with low water-holding capacity soils.

Farm 1, a mixed cropping/pasture system located mid-way between the ocean and inland limits of cropping, showed negligible impact on wheat yields under the HADCM3.1 future climate conditions for 'no change' in current practices, with slightly fewer high yielding crops indicated by a decreased 75th percentile yield. The median yield increased by 3% but the overall average yield fell by 5% under the HADCM3.1 projections, driven by a 12% reduction in 75th percentile crop yield (Figure 52a). Apart from this result, impacts on the riskiness of the operation were small, indicating that the decreases in wheat yields due to reduced average rainfall were largely offset by increases in productivity due to enhanced atmospheric CO_2 concentrations. The crop simulations using the drier MARK3 climate change projections were less positive, indicating a greater degree of yield reductions, particularly in higher yielding crops. For the "no change" option, the median wheat yield was reduced by 7% from 2330 kg/ha to 2174 kg/ha, and, combined with a 20% reduction in the 75th percentile yield, the average yield dropped from 2593 kg/ha to 2219 kg/ha (Figure 52b). Both changing the density of wheat sowing or retaining more crop residues showed neutral value as adaptation options, whereas opting for shorter growing season varieties suggested a potential method for regaining the high-yielding proportion of crops lost in a "no change" management response.

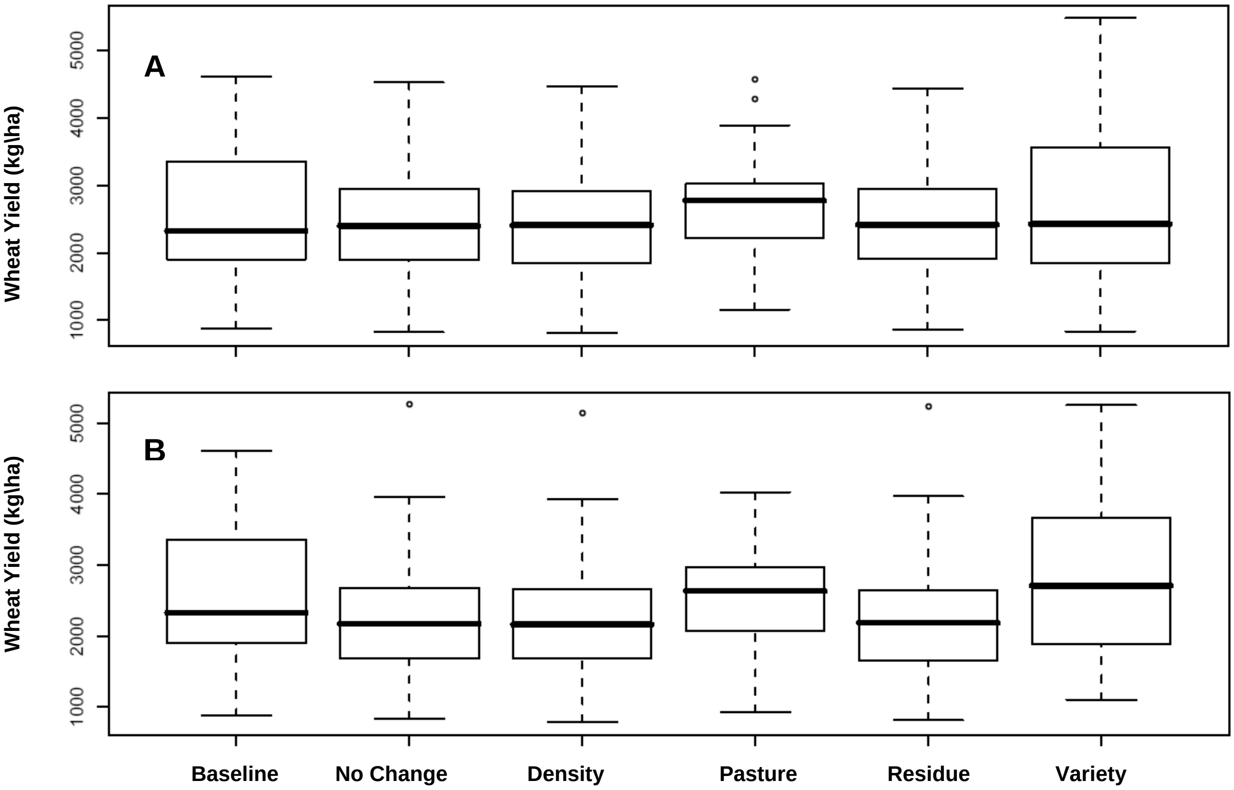


Figure 52: Mingenew Farm 1 adaptive strategy wheat yields for 2070 'high' scenario (A1T) as projected by a) HADCM3.1 and b) MARK3 GCM models – Simulated wheat yields (kg/ha) under current climate conditions ('baseline'- 1957 to 2006) compared with simulated wheat yields for a range of different adaptation options. These adaptation options include no change in current management 'No Change', reduced planting density 'Density', increasing pasture 'Pasture', increasing residue retention 'Residue', and choosing shorter season varieties 'Variety'.

Farm 2, a wheat-pasture system near the far edge of the cropping zone in the Mingenew District, was simulated to suffer significant reductions in wheat yields under both GCM projections for 2070, regardless of adaptation options simulated (See Figure 53). For the HADCM3.1 projections, median wheat yields were simulated to fall by 23% (from 3750kg/ha to 2887kg/ha) accompanied by a 20% fall in average wheat yields. The picture was even more severe under the MARK3 GCM projections, with average wheat yields falling by 34% for the "no change" management option. This continues the trend for this farm from the 2030 scenarios, with enhanced impacts. This farm is the least likely of the 4 Mingenew farms to receive locally-generated coastal showers, and is more reliant on the larger weather systems which are impacted by climate change to a greater degree. Additionally, soils on this farm are considerably poorer in terms of soil water-holding capacity than the other 3 regional farms.

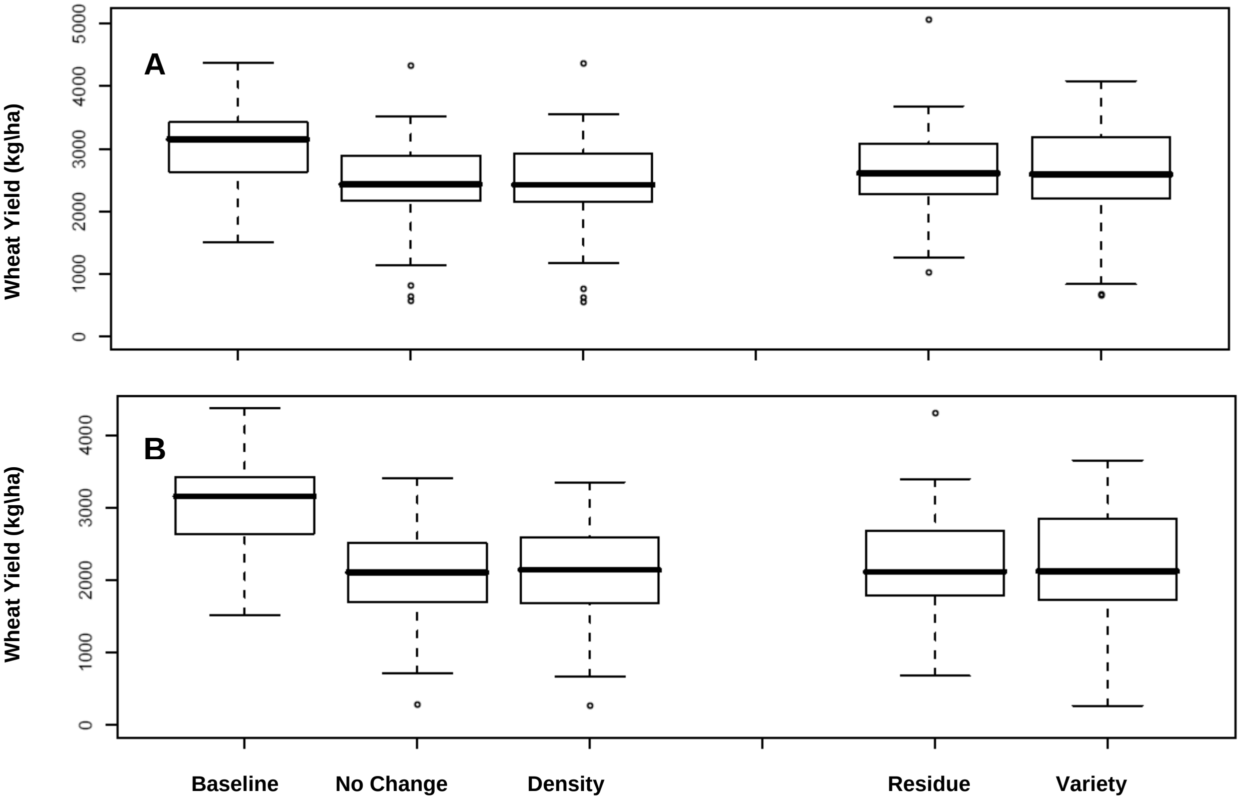


Figure 53: Mingenew Farm 2 adaptive strategy wheat yields for 2070 'high' scenario (A1T) as projected by a) HADCM3.1 and b) MARK3 GCM models – Simulated wheat yields (kg/ha) under current climate conditions ('baseline'- 1957 to 2006) compared with simulated wheat yields for a range of different adaptation options. These adaptation options include no change in current management 'No Change', reduced planting density 'Density', increasing pasture 'Pasture', increasing residue retention 'Residue', and choosing shorter season varieties 'Variety'.

Mingenew Farm 3 was classified as a mixed cropping system, and located in what is locally considered an excellent farming region with deep soils close to the coast. For the HADCM3.1 climate change projections for 2070, this farm stands to gain without any changes to current management, in terms of wheat production. The average yields are simulated to increase (3750 kg/ha up to 3847 kg/ha) accompanied by increases in the frequency of higher yielding crops, and decreases in the number of lower yielding crops. The overall riskiness of wheat production is forecast to reduce, and as mentioned previously this is likely due to the fact that with the HADCM3.1 model, projected rainfall reductions are not significant enough to overshadow the increased atmospheric CO_2 concentrations which serve to increase crop productivity (Figure 54a). Adaptation options considered were not notably more effective in increasing wheat yields, with the exception of the option to increase residue retention, but as discussed subsequently in the "Overall Gross Margins" section this option would result in decreased income from sheep grazing of residues, so the overall potential benefit may be negated.

Under the more severe climate change projections associated with the MARK3 model production is simulated to decline by 3% (from 3750 kg/ha up to 3637 kg/ha) under “no change” management. All subsequent adaption simulations indicated a reduction in low-yielding wheat crops across the range of adaptation options apart from changing to quicker varieties (Figure 54b). It is relevant to note that although ‘quicker varieties’ presented enhanced performance for Farm 1, it is not the case for Farm 3.

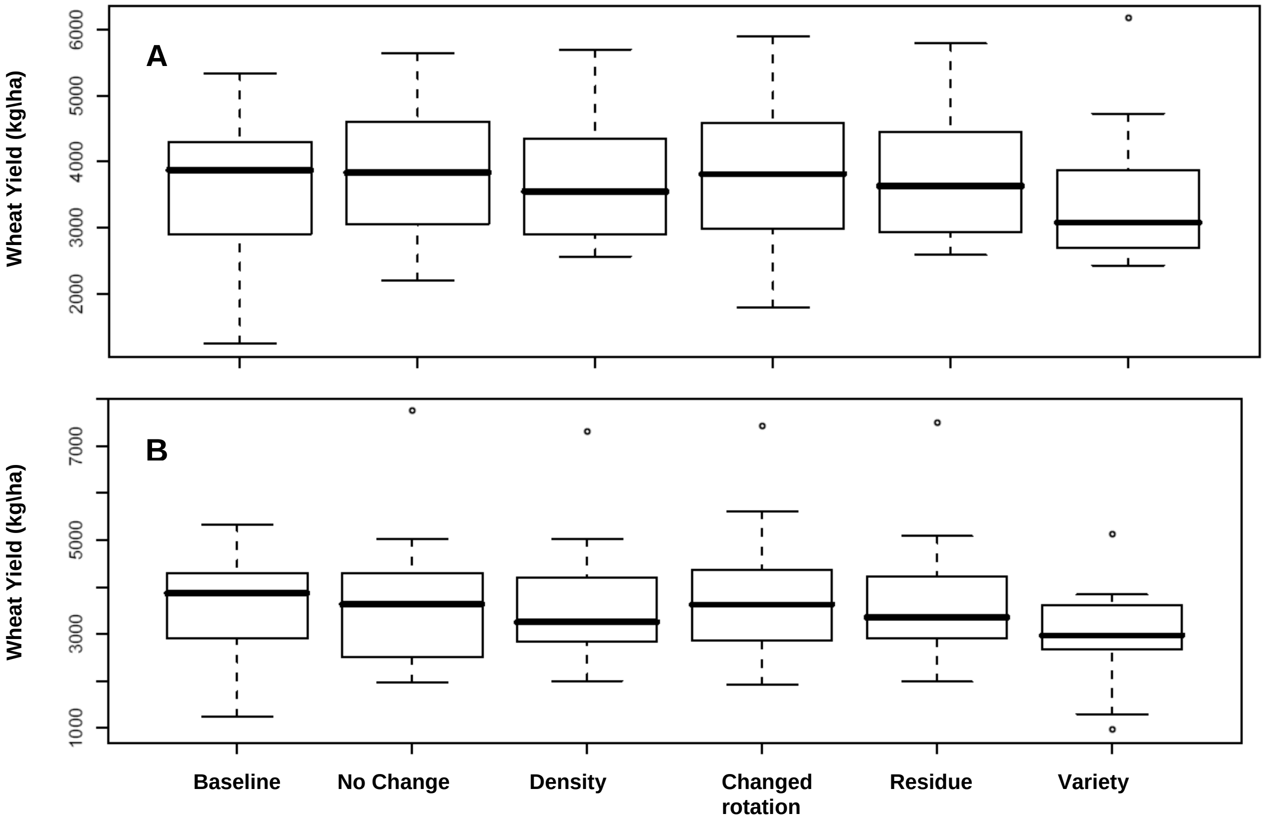


Figure 54: Mingenew Farm 3 adaptive strategy wheat yields for 2070 ‘high’ scenario (A1T) as projected by a) HADCM3.1 and b) MARK3 GCM models – Simulated wheat yields (kg/ha) under current climate conditions (‘baseline’- 1957 to 2006) compared with simulated wheat yields for a range of different adaptation options. These adaptation options include no change in current management ‘No Change’, reduced planting density ‘Density’, increasing pasture ‘Pasture’, increasing residue retention ‘Residue’, and choosing shorter season varieties ‘Variety’.

Mingenew Farm 4 is also classified as a mixed cropping system, and is located close to the coast. This farm has historically experienced very reliable ‘wheat-season’ rainfall, and has thus been regarded as a low-risk farming operation with good soils. Figure 55 shows that projected climate change derived from either the HADCM3.1 or MARK3 climate models will have a marginal impact on wheat production in this farming system (i.e. between 3 and 7% respectively). What is clear in both cases is an increase in production variation under warmer and drier conditions, with the fallow adaptation once again delivering median yield improvements compare with the ‘no change’ options for projected severe (MARK3) and less severe (HADCM3.1) rainfall declines.

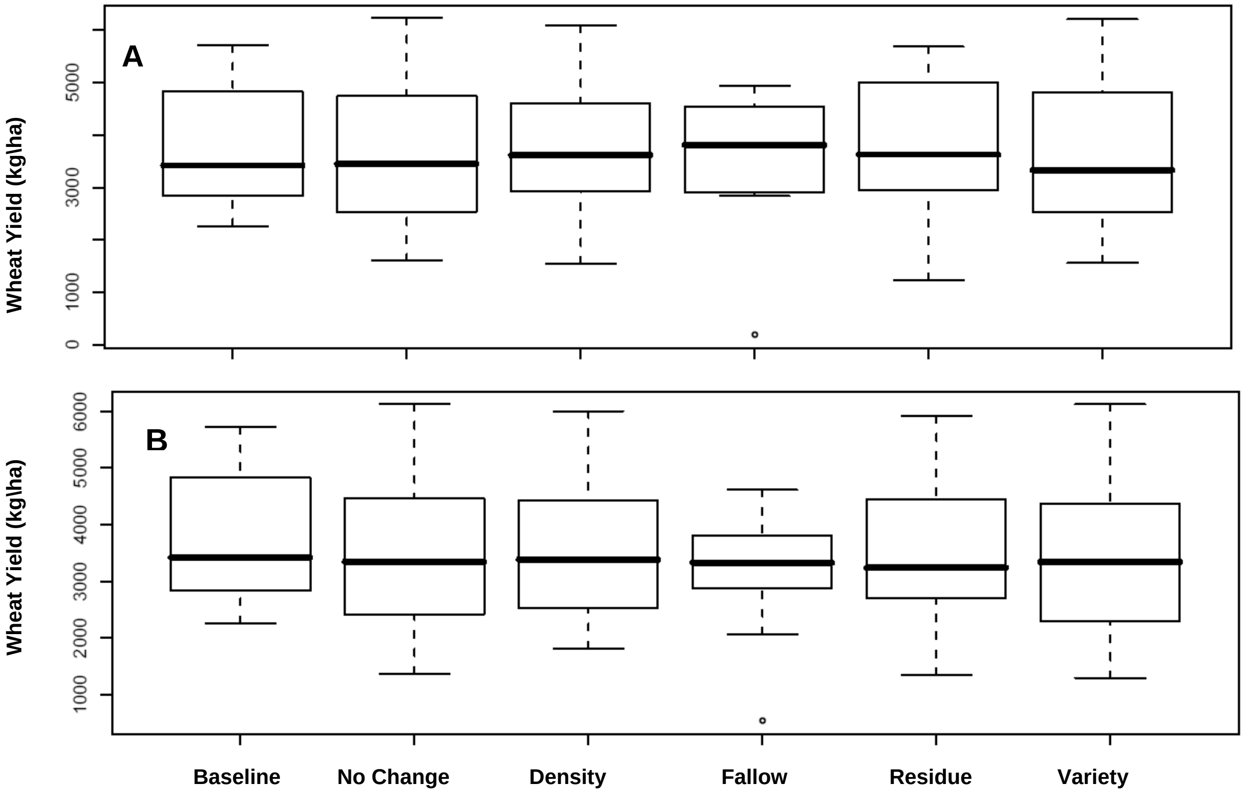


***Figure 55**: Mingenew Farm 4 adaptive strategy wheat yields for 2070 'high' scenario (A1T) as projected by a) HADCM3.1 and b) MARK3 GCM models – Simulated wheat yields (kg/ha) under current climate conditions ('baseline'- 1957 to 2006) compared with simulated wheat yields for a range of different adaptation options. These adaptation options include no change in current management 'No Change', reduced planting density 'Density', increasing pasture 'Pasture', increasing residue retention 'Residue', and choosing shorter season varieties 'Variety'.*

Overall gross margins

It is important to remember that the impact of climate change on wheat yields under various adaptation options – although a vital piece of information – is only one component in deciding if this is an appropriate opportunity to pursue in the future. Adaptations which improve the prospects for wheat production may have negative effects on other components of the rotation, or on the overall financial performance of the farm. For example, adding an extra fallow period into the rotation is likely to benefit subsequent crops, particularly if the soils can store appreciable amounts of water. But although the subsequent crop may achieve greater average yields, it may not be sufficient to make up for the lost crops in the rotation. To determine if the yield benefits outweigh the lost crops in the rotation examined, at a coarse level, the economic implications of introducing fallows or other adaptation options. This is a major question in analysing climate change adaptation options, but requires detailed information and knowledge of the individual farm business.

Within the scope of this research project, we have taken two approaches.

1. In the Birchip region, Randall-McGuchie (an agricultural economics consultancy) has been contracted to conduct a full scale evaluation of

simulated results, taking into account detailed farm economics, commodity and cost prices, and opportunity costs such as mentioned above (e.g. fallows).

2. Simple gross margin analyses have been conducted on the whole paddock rotation for one farm in each of the case study regions, for one climate change scenario. These results are presented below:

Figures 56 to 58 compare the impact of introducing the adaptation options in terms of wheat productivity (Figure 56a, 56a, 57a) and gross margins (Figure 56b, 57b, 58b). These comparisons have been made for a single farm in each of the three study regions using the projected climate change associated with the 2070 HADCM3.1 'high' A1T scenario. Figure 56 shows the wheat yield and paddock gross margin comparison for **Jandowae Farm 1.** The baseline rotation is millet-millet-wheat-wheat-sorghum. Looking at the wheat yield box plots in Figure 56a, the increasing fallow option looks to be most viable with the highest median yield gains compared with the 'no change' and other adaptation options. However the box plots in Figure 56b indicate that from the perspective of median AU$ returns, pursuing the 'residue' option maybe most economically viable. Also, from Figure 56a it would appear that the decreasing planting density adaptation option provides no gains over no change in management practice, however Figure 56b indicates that reducing crop density will decrease the number of years with lower-end gross margins, while increasing the number of years with higher-end gross margins.

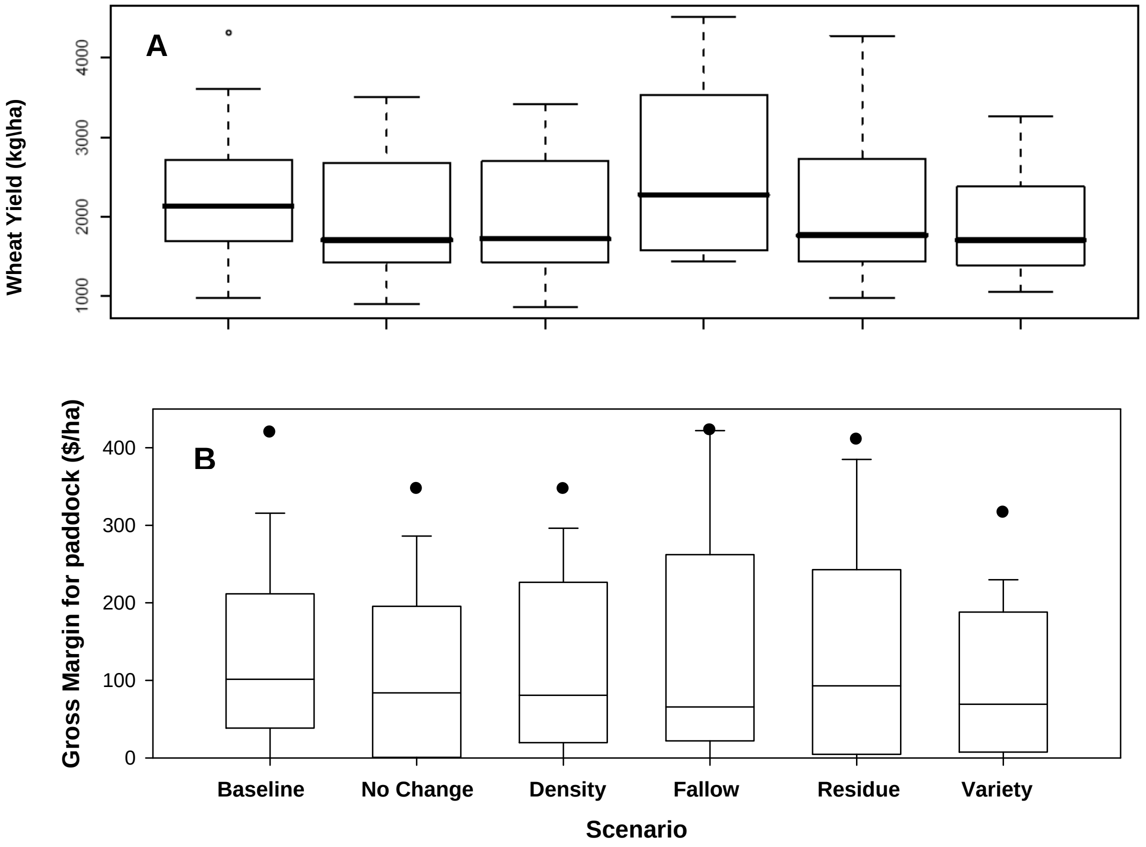


Figure 56*: Jandowae Farm 1: comparison of adaptive strategies for HADCM3.1 2070 'high' scenario (A1T) from the perspective of a)* ***wheat yields*** *(kg/ha) and b) whole paddock* ***gross margins*** *(including yield impacts on other crops in the rotation, and the effect of fallow periods).*

Figure 57 shows the comparison for **Birchip Farm 1**, a wheat-pasture operation, with a baseline treatment consisting of wheat every second year, interspersed with a year of weedy pasture for grazing. As for the Jandowae farm above, the wheat yield box plots in Figure 57a point to the potential benefit of increasing pasture in the rotation from 1 year in 2, to 2 years in 3. Looking at the whole paddock returns however, it can be seen that the increased pasture adaptation option has the lowest median return of all adaptation options examined (Figure 57b). In this case reducing planting densities resulted in slight median and 75th percentile gains compared with the "no change' case.

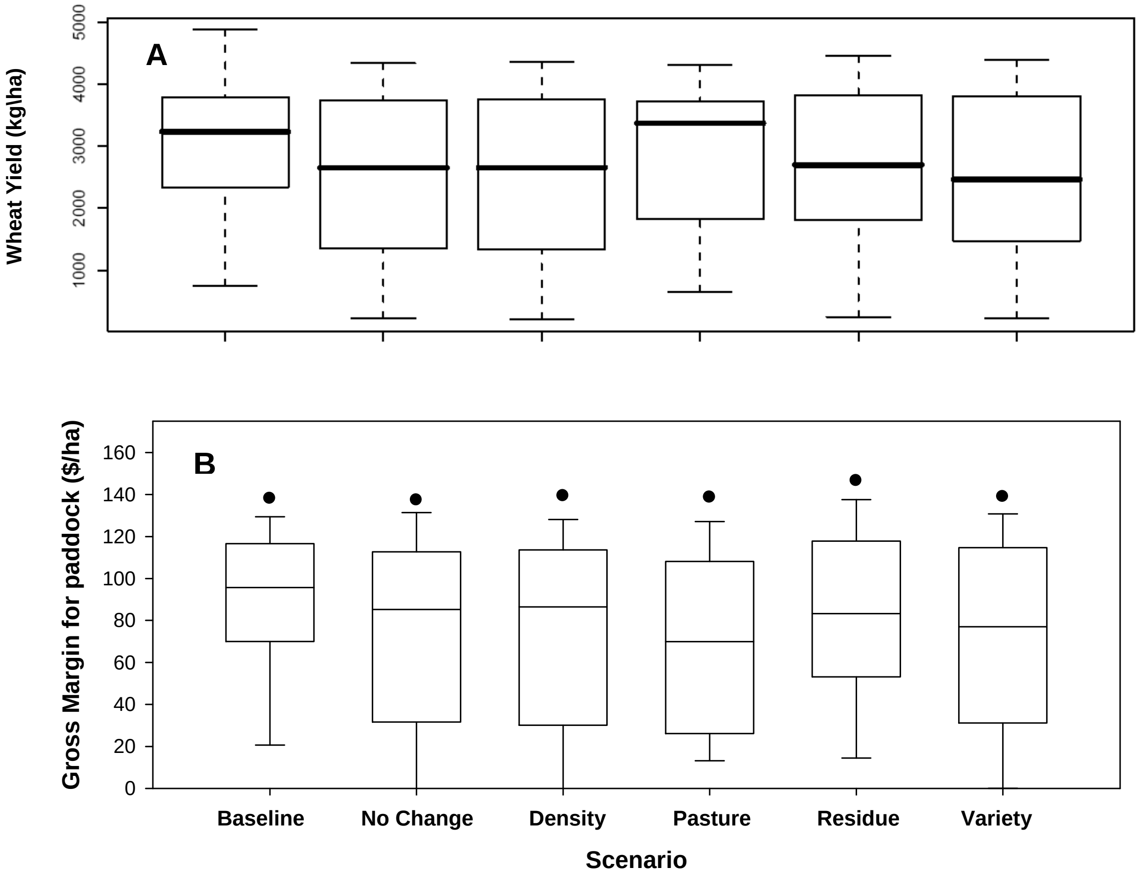


Figure 57: Birchip Farm 1: comparison of adaptive strategies for HADCM3 2070 'high' scenario (A1T) from the perspective of a) ***wheat yields*** *(kg/ha) and b) whole paddock* ***gross margins*** *(including yield impacts on other crops in the rotation, and the effect of fallow periods).*

Mingenew Farm 4 (Figure 58) shows a similar outcome to the previous two comparisons, with the 'fallow', adaptation option providing the best production benefits but worst gross margin returns. This suggests that in all three cases the production gains from increased fallows do not compensate for the loss of crop revenue. Again decreasing planting density presented the best gross margin returns compared against the 'no change' case, with both slightly higher median and 75th percentile gross margins. This is likely due to the fact that although median yields are reduced compared with "no change", the reduced cost for seed and reduced impact on subsequent crops results in an increased overall return for the paddock.

These three examples serve to illustrate that simple paddock economics can provide different insights into the effectiveness of adaptation options compared with just examining productivity changes alone. A full assessment of adaptation options requires integration of more detailed economic analysis than provided in this project section, synthesising the outputs from crop models like APSIM with relevant economic inputs to provide a more realistic assessment of the criteria on which a farmer might base his decision to change management practices.

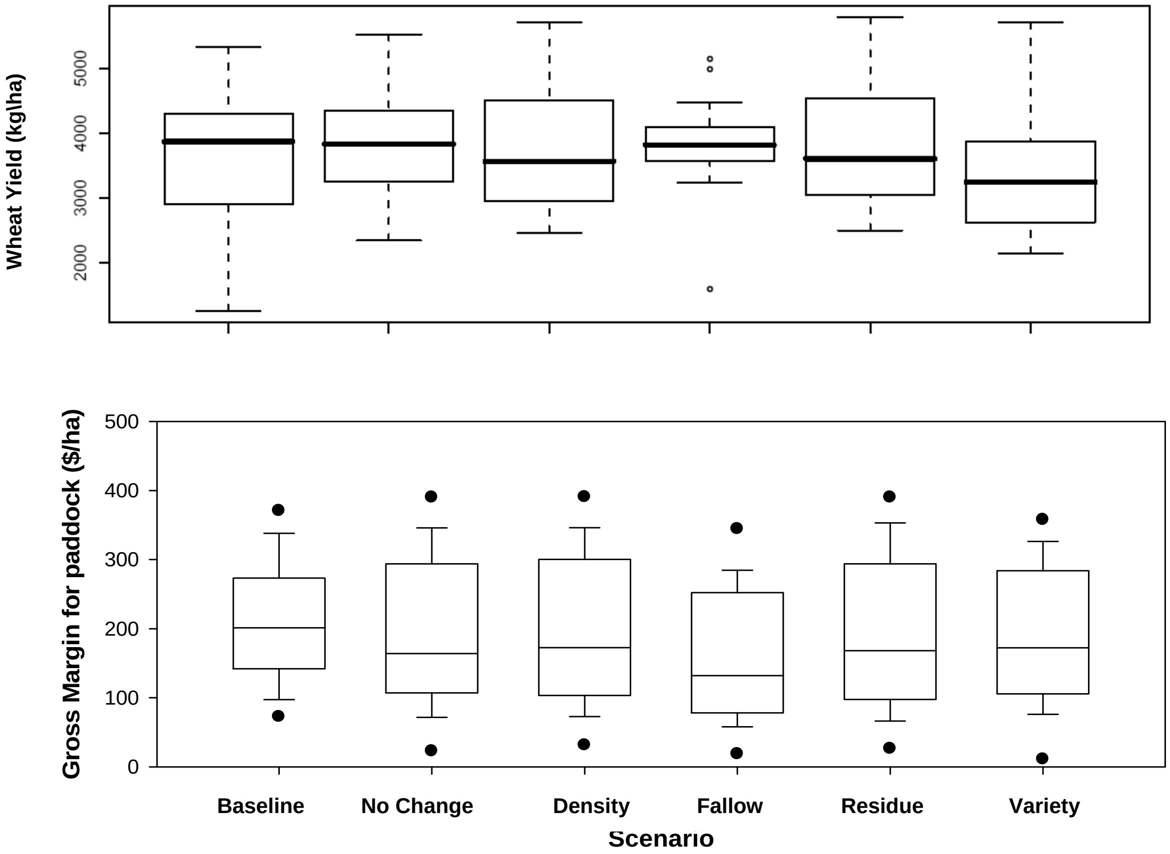


Figure 58: Mingenew Farm 4: comparison of adaptive strategies for HADCM3 2070 'high' scenario (A1T) from the perspective of a) ***wheat yields*** *(kg/ha) and b) whole paddock* ***gross margins*** *(including yield impacts on other crops in the rotation, and the effect of fallow periods).*

Spraying impacts results

Analysis revealed that under current climate conditions optimal spraying times exist between April and August for the Jandowae region, between May and September for the Mingenew region and between April and October for the Birchip region (Figure 59).

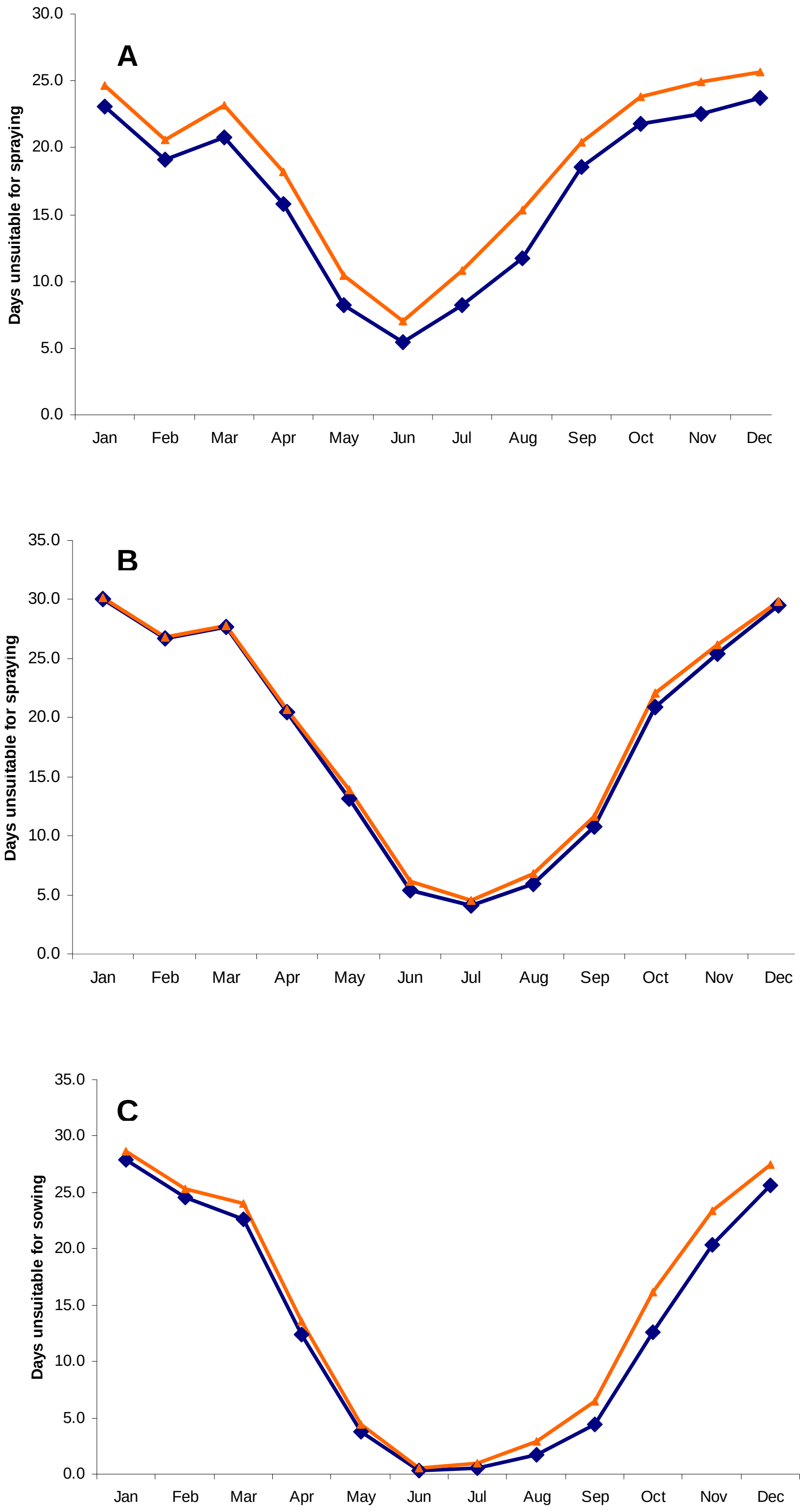


***Figure 59**: Average number of days unsuitable for spraying in each month, under current (blue) and 2030 conditions (orange) for a) the Jandowae region; b) the Mingenew region; and c) the Birchip region.*

The impact on the number of days suitable for spraying was examined by modifying the temperature and relative humidity in each of these three regions according to changes produced by the CSIRO MARK3 model initiated with the A1T emission scenario at 2030. The most significant impact appears in the Jandowae region with an additional 26 days unsuitable for spraying (13% increase). Smaller impacts are simulated in both the Mingenew and the Birchip regions with a 7 day (3%) and 17 day (11%) increase respectively.

DISCUSSION

Climate Trends

Recent analyses by Karoly and Braganza (2005a,b) conclude that future temperature changes at a regional scale in Australia are very unlikely to be due to natural climate variations alone. They conclude that increased atmospheric concentrations of greenhouse gases are likely to have been a significant contributor to the observed warming. The analyses reported here, at a finer scale, also indicate significant and sustained change in many climate variables. In many cases (e.g. temperature increases around Jandowae) these past trends are consistent with projections of rainfall and temperature change expected on the basis of outputs from Global Climate Models. This is true even where the historical trends are not statistically significant due to high year to year variability. In summary all three of the case study regions have displayed warming in average temperatures, with Jandowae and Mingenew regions experiencing statistically significant declines in annual rainfall.

However, in some cases (e.g. minimum temperatures in the southern sites) the trend is unexpectedly downwards: in which case there are inconsistencies with predictions of future changes. In the Birchip region the decline in annual minimum temperature (i.e. -0.02 ^{o}C/decade) combined with a strong trend of increase in the date of the last frost (4.9 days/decade) resulted in considerable increase in the exposure to frost risk (Figure 17). In the Mingenew region the occurrence of frosts has not been seen as a significant risk given that on average this region experienced only one frost per year (between 1960 to 2006). However, since 1990 this region has also shown a slight (not statistically significant) increase in the frequency of frosts. This is not the case with the Jandowae region, where annual minimum temperatures have increased by 0.18^{o}C/decade and a significant reduction in the number of frosts per year (-1.9 frosts/decade) has occurred.

Consequently, in these cases simple extrapolations of past change may be inappropriate as a basis for exploring management adaptations. For this reason it is critical that we begin to understand the current drivers of existing historical trends and ensure that these learnings are included in our current suite of GCMs. If these regional interactions with other drivers (such as topography, etc) are not considered then the projections on which we determine adaptation options may lead to mal-adaption.

Climate change adaptation

There is now firm evidence that the global climate has changed over the past century and will continue to change throughout the 21st century in response to continued growth in global greenhouse gas emissions (IPCC, 2007). There is also growing evidence that current changes in Australian regional climate are linked to both human activities and natural variability (CSIRO, 2007; IPCC, 2007) and that some current patterns of change in Australia (particularly mean temperature but also rainfall) are consistent with those projected (Cai and Cowen, 2007; Timbal *et al*., 2006). There is a growing concern that changes in the climate system will have detrimental impacts on some agricultural systems. Agricultural systems may be negatively impacted due to changes in water availability, as well as heat stress and pest, disease or weed pressures (IPCC 2007). For this reason, a strong incentive exists to enhance the adaptive capacity of agricultural systems in order to deal with further changes expected as a result of future climate change. The vulnerability of an agricultural system to long-term changes in temperature or precipitation, or the frequency and magnitude of extreme weather events, is greatly influenced by its adaptive capacity (Bradshaw *et al.*, 2004).

There are many potential adaptation options available that may serve to offset potentially negative impacts from modest climate change, and often these include variations of existing climate risk management. Identifying these options requires extensive participatory research which acknowledges that much of the expertise resides with the farmers themselves. By bringing their practical knowledge into the assessment, a more comprehensive range of adaptations can be explored that are practical and more realistic in terms of the costs and benefits involved in management (Howden *et al.*, 2007).

However, there are limits to the effectiveness of tactical adaptation under more severe climate changes. Hence, more systemic changes in resource allocation are needed, such as targeted diversification of production systems and /or land use change.

Recent research on adaptation has followed a variety of paths, with the main focus on the evaluation of the merit of general adaptation options. This research has identified in broad terms the following adaptation options for cropping systems:

- "Altering inputs such as varieties/species to those with more appropriate thermal time and vernalisation requirements and/or with increased resistance to heat shock and drought, altering fertilizer rates to maintain grain or fruit quality consistent with the prevailing climate, altering amounts and timing of irrigation and other water management.
- Wider use of technologies to ''harvest'' water, conserve soil moisture (e.g., crop residue retention), and use and transport water more effectively where rainfall decreases.
- Managing water to prevent water logging, erosion, and nutrient leaching where rainfall increases.
- Altering the timing or location of cropping activities.
- Diversifying income through altering integration with other farming activities such as livestock raising.
- Improving the effectiveness of pest, disease, and weed management practices through wider use of integrated pest and pathogen management, development, and use of varieties and species resistant to pests and diseases and maintaining or improving quarantine capabilities and monitoring programs.
- Using climate forecasting to reduce production risk" (Howden et al., 2007, p19693).

Rather than simply identifying all possible adaptations for managing climate-related risks, this research project has sought to evaluate the suitability of adaptation options according to criteria such as production impacts (i.e. yield) and, in more limited applications, simple gross margin analysis (i.e. Birchip, Mingenew and Jandowae regions) and farm budgets (i.e. limited to the Birchip region). This research project has examined these broad scale adaptation options, and, through engagement with production groups and individual farmers, has evaluated adaptation options that, while achieving similar broad goals, are tailored to individual farming systems. After being exposed to projected climate trends for their regions, farmers were asked to identify a range of adaptation options they would consider implementing in order to reduce possible negative impacts on production. A range of both tactical and strategic responses were identified (Table 1) and a subset of four tactical adaptation options were assessed at each site. These included:

- increasing fallow or pasture component;
- reducing planting density;
- changed crop rotations (limited cases);
- selecting shorter season crops; and
- increasing crop residue retention.

The impacts of implementing these adaptation options was considered under both a modest global warming scenario (i.e. linked to the A2 SRES scenario) and a more extensive global warming scenario (i.e. linked to the A1T SRES emission scenario) as projected by two different GCMs. Whilst this approach may not capture all of the potential uncertainty regarding the extent of future climate change, our choice of emission scenarios and models (i.e. HADCM3.1 and MARK3) provides confidence that the uncertainty we present is reasoned and robust.

The results from this study suggest that some adaptation options provide resilience to both modest and more extensive climate change across much of Australia. These adaptation options include the implementation of additional ‘fallow’ or ‘pasture’ components in the rotation and the enhancement of current residue retention practices. The additional ‘fallow’ or ‘pasture’ adaptation served to improve median yield production by between 4 to 55% for a modest global warming scenario, depending on region and positioning of the fallow in the rotation. The greatest improvements in median yield were returned in the Jandowae region (i.e. up to 55%) as the soils in this region have greater water holding capacity than the other two regions and thus benefit more from improvements in soil water retention. The management of water affects most crop production. Water is required in the root zone for germination, plant water uptake, transpiration, and nutrient absorption by the roots, root growth, soil microbiological and the chemical processes that aid in the decomposition of organic matter as well as the mineralization of nutrients (Izuno, 2002).

At the same time, the root zone must be sufficiently dry to ensure adequate aeration and root extension and to allow field activities such as planting, cultivating, fertilization, pesticide and herbicide applications, as well as harvesting operations (Izuno, 2002). In the Mingenew region two of the case study farms were exposed to too much water in the root zone associated with dryland salinity. For this reason fallowing was not an adaptation volunteered by farmers and implementation of ‘residue’ retention resulted in simulated declines in median yields of between 3 and 9%. On these farms the projected reduction in rainfall had beneficial impacts on the lowest 25% of yields as a result of removing excess water from the root zone.

Improving crop and farm system water use efficiency (WUE) has been an important consideration of Australian farmers over the past 30 years. Many improvements in WUE have been attained through changed dryland farming practices such as minimum disturbance planting, varietal changes, better managed phase changes (pasture to crop and back) and summer fallow management (stubble and weeds).

These adaptation options have had varying degrees of success in Australia depending on the regional constraints and this research suggests that these will be a continuing challenge in the future. These constraints include:

- “Physical - soil types, depths, and characteristics, field layout, water sources and sinks, water distribution systems, farm technology and machinery.
- Climatic - heat and other extremes, drought potential, rainfall amounts and intensities, vapour pressure deficit and sunshine.
- Economic - material availability, labour cost and availability, and investment capacity.
- Social - governmental regulations/incentives, environmental concerns, safety considerations” (Izuno, 2002).
- Information – information gaps, communication issues.

Some adaptation options proved of little value in improving production across all three case study regions. These included reducing planting density and changing crop variety. However in the case of changing crop density, this adaptation option did result in slightly better gross margin returns than did the implementation of additional pasture or fallows in the crop rotation. These results strongly indicate that both productivity and economic impacts must be considered in an integrated and realistic way in order to identify appropriate adaptations options at individual farms and at a regional scale.

Changing to shorter season varieties proved an inadequate adaptation option in both the Jandowae and Birchip regions, resulting in lower simulated yields compared to yields from no change in current management, in most cases. In the Mingenew region this adaptation option proved more valuable, resulting in higher median yields than yields from no change in current management. These results should be treated with some caution, as the choice of shorter season variety was dictated by the individual farmer response. The results may reflect a less appropriate choice of varieties in both the Birchip and Jandowae regions, and thus selection of different crop varieties should not be discounted based on the results from this study. A more appropriate way of variety selection should involve both farmer expert knowledge and modelling studies to optimise varietal selection.

Changed crop rotation was an adaptation option examined on two farms, one in the Birchip region and one in the Mingenew region. Results were mixed. In the Birchip region changing the rotation to remove fababeans and include fallows before canola and wheat served to improve the yields in the lowest 25% of years, but also reduced yields in the upper most 25% of years, most likely due to less soil nitrogen being available in a rotation without the soil nitrogen-fixing fababeans. For this reason the adaptation option was successful at reducing the variability of wheat yields but resulted in lower median yield over all (i.e. 12% lower than the baseline yield of 3730kg\ha). In the Mingenew region the changed rotation included shortening a 13 year rotation to a seven year rotation by reducing the number of lupin and oat crops. This adaptation option had the same effect as in the Birchip region (i.e. improved lowest 25% of yields and reduced upper 25% of yields), however the impact on the upper 25% of simulated yields was not as significant, thus resulting in a 2 to 5% improvement in median yields compared to the 1957 to 2006 baseline. In both instances examination of the gross margin impacts showed improvements in gross margin returns when compared against the ‘no change’ in management option. For

Farm 4 in the Birchip region changing the crop rotation resulted in a 5% improvement in median gross margin returns compared to the 'no change case' (i.e. an additional $4 per hectare per year). For Farm 3 in the Mingenew region shortening the crop rotation resulted in a 7% improvement in gross margin returns (i.e. an additional $11 per hectare per year) compared with the 'no change' in management.

The evaluation of adaptation options across three regions, two emission scenarios and future climate predictions from two GCMs has highlighted that the success or failure of any adaptation option, in terms of offsetting potential future yield losses and maximising yield gains and economic returns, is the result of a complex interaction between soil types, field layout, farm technology and machinery, the extent of future climate change, labour cost and availability, and investment capacity.

We have shown that the adaptation options we have considered are most effective with small temperature increases (1 to 2°C) and rainfall declines (i.e. less than 10%), serving to offset losses or, in situations were rainfall is not limiting, raising yields. (Figure 60). This has been demonstrated in earlier research (Howden and Crimp 2005). Under modest temperature increases of 1 to 2°C yields may be raised by 6 to 12%. At higher temperatures further benefit was limited, particularly under scenarios with reduced rainfall. The greatest benefit from adaptation arose from adaptive management in response to higher rainfall scenarios where benefits of up to 16% were simulated (i.e. 4°C and 20% more rainfall) (Figure 60).

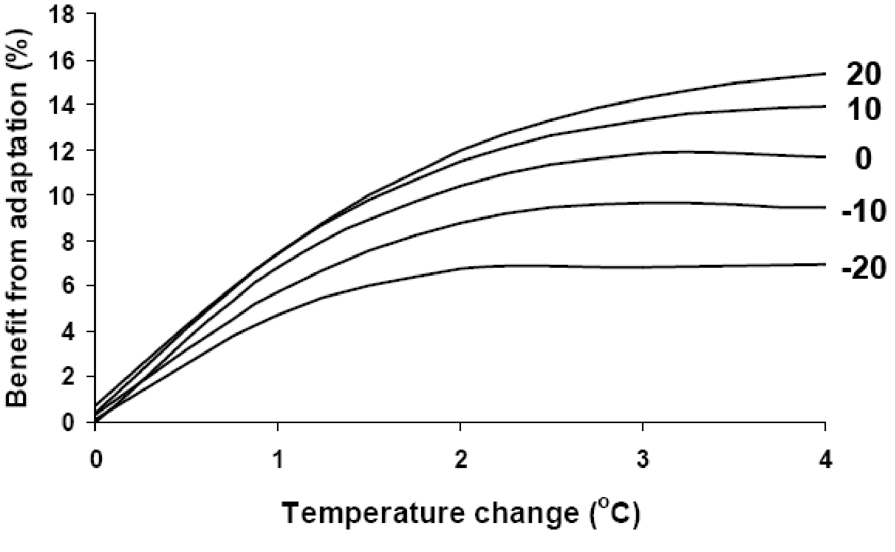


Figure 60: *National aggregated yield benefit (% increase) arising from practising adaptations for temperature increases up to 4°C and rainfall changes of +20, +10, 0, -10 and -20%. Temperature and rainfall changes were applied uniformly across the nation.* CO_2 *level was held at 350ppm.*

This and other studies have shown that there are limits to the effectiveness of incremental changes under more severe climate changes (Easterling *et al.*, 2007; Howden *et al.* 2007). Hence, more systemic changes in farming operations will also need to be considered, such as targeted diversification of production systems and livelihoods.

This project has attempted to aggregate a number of these drivers in order to provide a robust evaluation of adaptation options, but acknowledges that actual farm level decisions are seldom made with respect to just one stimulus.

The difficulty of accounting for the inevitable compounding effect of non climatic risks and opportunities represents just one of many barriers to improving our understanding of the likely adaptive response of farmers to anticipated climate change. We examine this issue in more detail in subsequent sections of this discussion.

Climate change impacts on spraying opportunities

The frequency of climatic conditions unsuitable for spraying agri-chemicals appears likely to increase due to climate change. This increase could be around 30% by 2030 if potential changes in both ΔT and wind speed are considered. In this study we have shown an increase in unsuitable spraying conditions of up to 13% considering only potential changes in ΔT. This reduction in opportunities to spray could be a particular concern where climate change is increasing agronomic risks via: 1) the potential reduction in effectiveness of glyphosate under elevated CO_2 concentrations for some weed species (Ziska and Teasdale 2000); 2) the relative competitiveness of weeds is increased as a result of climate changes; 3) the range and occurrence frequency of pests, diseases or weeds is increased; or 4) increased damage from pests due to increases in pests' dry matter intake requirements as a result of elevated CO_2 increasing the carbon to nitrogen ratio of leaves (IPCC 2007b). There are likely to be a range of adaptations to these changed conditions, including: coarser nozzles, reduced application speed, use of adjuvants to alter droplet characteristics, lowered boom height, changed nozzle angle and spray pressure and increased water volume. All of these have implications for scheduling, costs of operations and water use and not all options are well enough understood to ensure consistent and effective results.

There are some caveats for this assessment including: 1) we have not explicitly included the change in variance in wind and temperature conditions that may arise; and 2) we have used climate simulations from only one GCM. Other GCMs will show different changes in the driving climate variables. A more comprehensive assessment of this climate change risk factor is required.

Scaling climate adaptation strategies from farm to regional scale

Many of the climate change adaptation studies undertaken to date have focussed on evaluating adaptation options at the farm scale. Whilst this approach can help inform decisions by farmers and agribusiness over shorter timeframes it falls short of providing evaluation of long-term, strategic, timescales (Howden *et al.*, 2007).

For this reason it is important to align the scales (spatial, temporal, and sectoral) and reliability of the information with the scale and nature of the decision (Howden *et al.*, 2007). For example, short-term climate adaptation by farmers may be accomplished by taking into account local climate trends if there is a strong correlation between these trends and projected climate changes. However, farmers may find limited utility in long-term projections of climate, given the high uncertainties at the finer spatial and temporal scales at which their decisions are made (Howden *et al.*, 2007; Meinke and Stone, 2005).

In contrast, the general trends at longer time and larger spatial scales, which are able to be more reliably projected with current climate models, may be quite useful for input into policy and investment analyses, provided potentially critical factors are incorporated such as changes in climate extremes (Howden *et al.*, 2007).

A significant benefit from adaptation research may be to understand how short-term response strategies identified by farmers may link to long-term options to ensure that, at a minimum, management and/or policy decisions implemented over the next one to three decades do not undermine the ability to cope with potentially larger impacts later in the century.

To achieve this we need to ensure that a range of other drivers of change are also considered in overcoming existing environmental, economic, informational, social, attitudinal, and behavioural barriers to the implementation of adaptation. The following is a suggested approach to beginning to deal with these barriers, building adaptive capacity and changing the decision environment to promote adaptation actions, extracted from Howden *et al.*, 2007.

1. "To change their management, enterprise managers need to be convinced that projected climate changes are real and are likely to continue. This will be facilitated by policies that maintain climate monitoring and by communicating this information effectively, including targeted support of surveillance of pests, diseases, and other factors directly affected by climate.

2. Managers need to be confident that the projected changes will significantly impact on their enterprise. Policies that support the research, systems analysis, extension capacity, industry, and regional networks that provide this information could thus be strengthened. This includes modelling techniques that allow scaling up knowledge from gene to cell to organisms and eventually to the management systems and national policy scales.

3. Technical and other options necessary to respond to the projected changes need to be available. Where existing technical options are inadequate, investment in new technical or management strategies may be required (e.g., improved crop, forage, livestock, forest, and fisheries), including biotechnology. In some cases, old approaches can be revived that may be suited to new climate challenges.

4. Where climate impacts may lead to major land use change, there may be demands to support transitions such as industry relocation and migration of people. This may be achieved through direct financial and material support, creating alternative livelihood options with reduced dependence on agriculture, retraining and providing employment to the more vulnerable.

5. New infrastructure, policies, and institutions could be developed to support new management and land use arrangements. Options include enhancing investment in new infrastructure and efficient water use technologies; ensuring

appropriate transport infrastructure and examine alternative markets for products and inputs.

6. Importantly, policy must maintain the capacity to make continuing adjustments and improvements in adaptation by ‘‘learning by doing’’ via targeted monitoring of adaptations to climate change and their costs, benefits, and effects” (Howden *et al*., 2007, p19694 and p19695).

In conclusion it would seem that identifying appropriate adaptation options is not enough. There is clearly a need to better understand the likely farmer uptake of climate change adaptation options by understanding not only the potential biophysical impacts but also the economic and social impacts. This will require a greater appreciation of the human decision-making and behavioural responses to these impacts.

APPENDIX A

Farmer	*Control*	*Increased pasture/fallow*	*Reduced planting density*	*Shorter season crops*	**Keep residue**
Jandowae					
Predominantly winter cropping, with some summer crops	m-m-w-w-s (fallow before sorghum if sw low)	m-m-fal-w-s	“	Replace: Wheat: sunco w /hartog Sorghum: buster w/ early Millet: only one cultivar available	“
Predominantly summer cropping with some winter crops	Opportunistic – based on available water	Increase fallow after winter crop	“	Replace: Wheat: sunco w /hartog Sorghum: buster w/ early Chickpea: amethyst no change	“
Cotton and wheat cropping system	cott-w-cott-w-s (wheat is replaced by chickpea under good early sw conditions)	cott-w-fal-cott-w-fal	“	Replace Wheat: yitpi w/ tamaroi Chickpea: amethyst – no change: quickest already Sorghum: buster w/ early Cotton: siok w/ sica	“
Birchip					
Wheat/Pasture system	w-pas	w-pas-pas	“	Wheat: Replace kellalac w/ sunlin, yitpi w/ bowerbird, leave silverstar the same	“
Mixed cropping/grazing system	c-w-w-luc-luc-luc-luc-w	c-fal-w-w-luc-luc-luc-luc-fal-w	“	Wheat: As above Canola: replace ‘mystic’ w/ ‘early’ Lucerne: leave as ‘trifecta’	“
Mixed cropping system	c-w-b-fal	c-fal-w-b-fal	“	Wheat: As above Barley: replace ‘sloop_vic’ with ‘keel’ Canola: replace ‘mystic’ w/ ‘early’	“
Mixed cropping system	fb-w-c-w-o-o-w	fb-fal-w-c-fal-o-o-w and w-fal-c-o-o-fal-w	“	Wheat: As above Canola: replace ‘mystic’ w/ ‘early’ Fababean: continue with ‘fiord’	“
Wheat/Pasture system	w-pas (oats/medic pasture)	pas-w-pas	“	Wheat: As above Canola: replace ‘mystic’ w/ ‘early’	“

Farmer	*Control*	*Increased pasture/fallow*	*Reduced planting density*	*Shorter season crops*	**Keep residue**
Mingenew					
Mixed crop/Pasture system	w-b-fp-w-pas	w-pas-b-fp-w-pas	All sown crops - establishment reduced by 30%	Replace: calingiri w/ wyalkatchem, wyalkatchem & bonnie_rock w/ westonia Replace: parafield field pea w/ parvie field pea	Retain all residues after harvest
Wheat/Pasture system	w-pas	w-pas-pas	“	Replace: calingiri w/ wyalkatchem, bonnie_rock w/ westonia	“
Mixed cropping system	w-l-w-l-w-l-w-l-w-l-o-o-l	w-l-w-l-o-o-l	“	Replace: calingiri w/ wyalkatchem, bonnie_rock w/ westonia Replace: tanjil lupins w/ belara lupins	“
Mixed cropping system	w-c-w-fb	w-c-fal-w-fb-fal	“	Replace: bonnie_rock & wyalkatchem w/ westonia	“

w - wheat
b - barley
o - oats
c - canola
m - millet
s - sorghum
l - lupins
fb - fababeans
fp - field peas
luc - lucerne
pas - pasture
fal - fallow

APPENDIX B

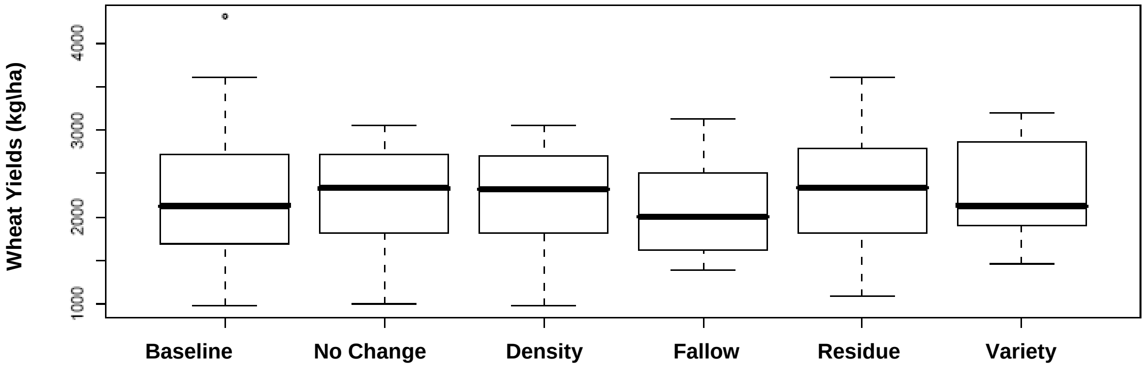


Figure 1: *Jandowae (Farm1) – Simulated wheat yields (kg/ha) for a predominantly winter cropping and some summer crops system under current climate conditions (baseline- 1957 to 2006) compared with simulated wheat yields under 'mid' range climate change scenario from the MARK3 climate model projections for different management options in 2030. These include no change in current management 'No Change', reduced planting density 'Density', increasing fallow 'Fallow', increasing residue retention 'Residue' and choosing shorter season varieties 'Variety'. The lower and upper edges of the box represent the 25th and 75th percentile yield values, the black line represents the 50th percentile yield and the upper and lower whiskers represent the 10 and 90 percentile yield values.*

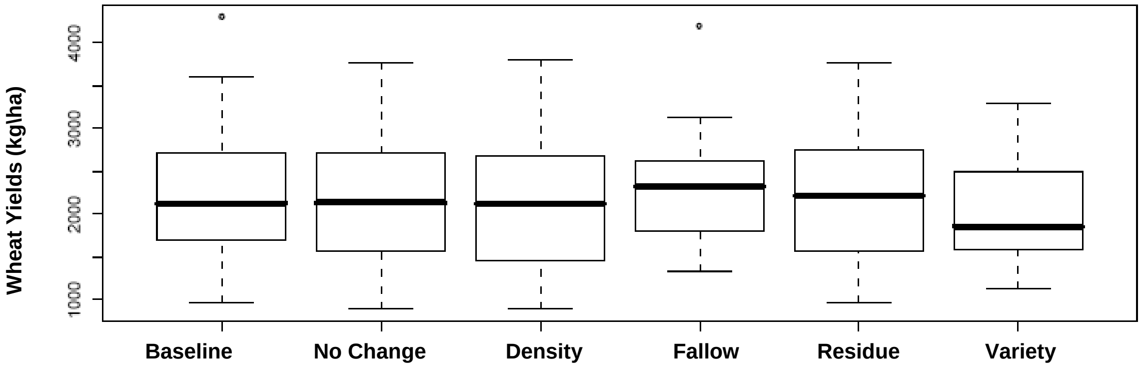


Figure 2: *Jandowae (Farm2) – Simulated wheat yields (kg/ha) for a predominantly winter cropping and some summer crops system under current climate conditions (baseline- 1957 to 2006) compared with simulated wheat yields under a 'high' range climate change scenario from the MARK3 climate model projections for different management options in 2030.*

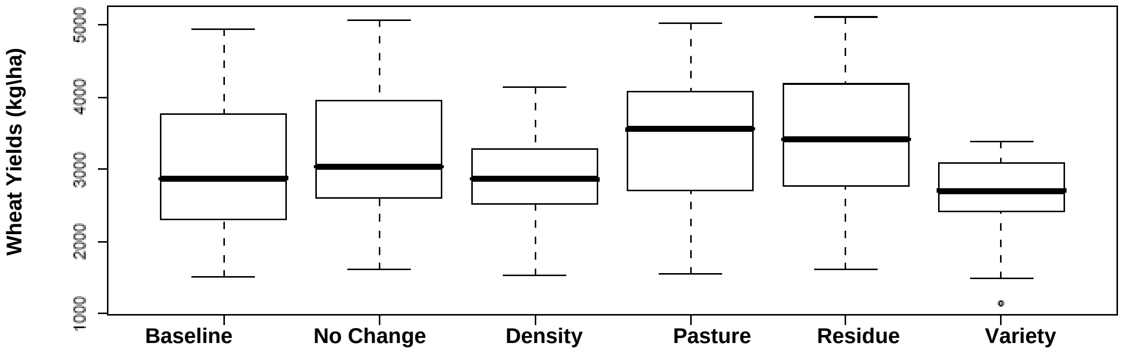


Figure 3: *Jandowae (Farm 3) – Simulated sorghum yields (kg/ha) for a predominantly summer cropping system under current climate conditions (baseline- 1957 to 2006) compared with simulated wheat yields under a 'mid' range climate change scenario from the MARK3 climate model projections for different management options in 2030.*

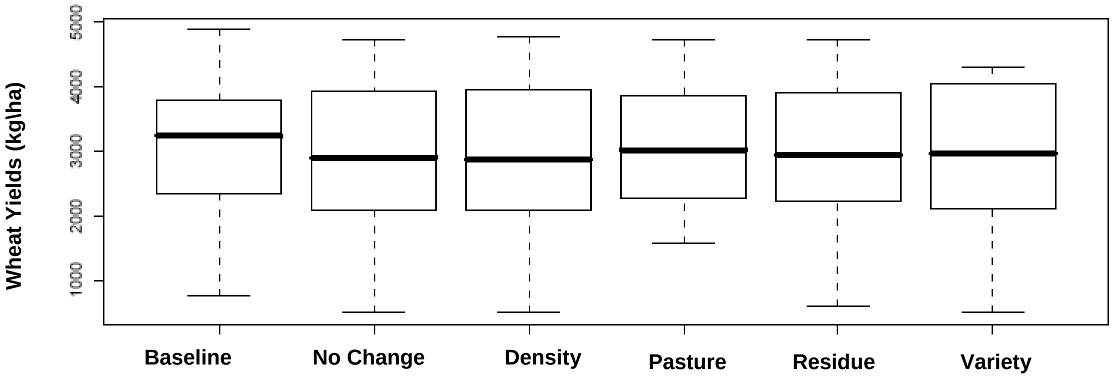


Figure 4: *Birchip (Farm 1) – Simulated wheat yields (kg/ha) for a wheat/pasture farming system under current climate conditions (baseline- 1957 to 2006) compared with simulated wheat yields under a 'mid' range climate change scenario from the MARK3 climate model projections for different management options in 2030.*

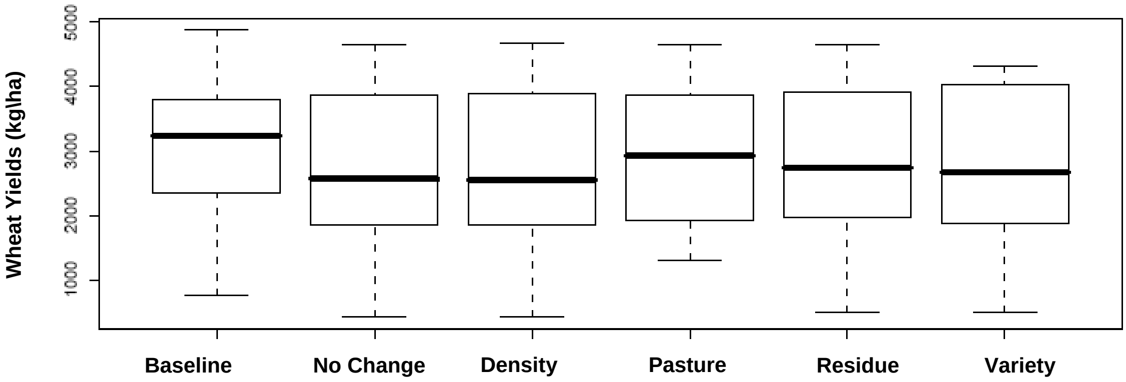


Figure 5*: Birchip(Farm 2) – Simulated wheat yields (kg/ha) for a wheat/pasture farming system under current climate conditions (baseline- 1957 to 2006) compared with simulated wheat yields under a 'high' range climate change scenario from the MARK3 climate model projections for different management options in 2030.*

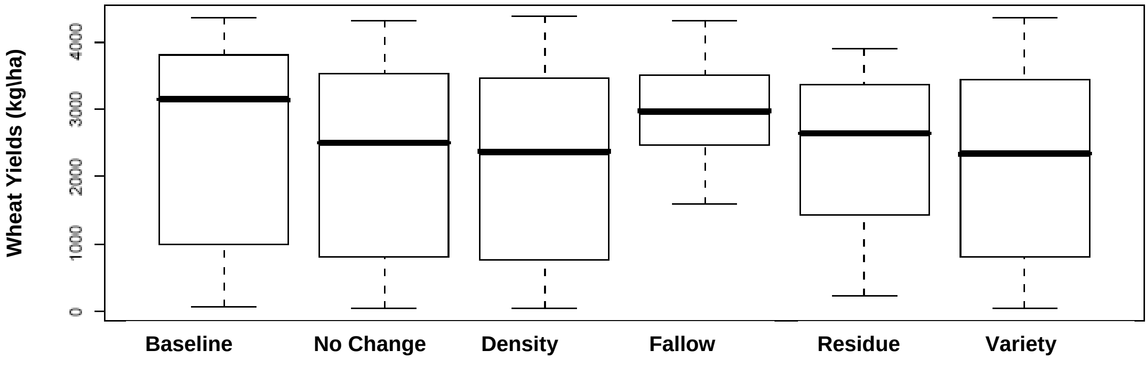


Figure 6*: Birchip(Farm 3) – Simulated wheat yields (kg/ha) for a mixed cropping/grazing farming system under current climate conditions (baseline- 1957 to 2006) compared with simulated wheat yields under a 'high' range climate change scenario from the HADCM3.1 climate model projections for different management options in 2030.*

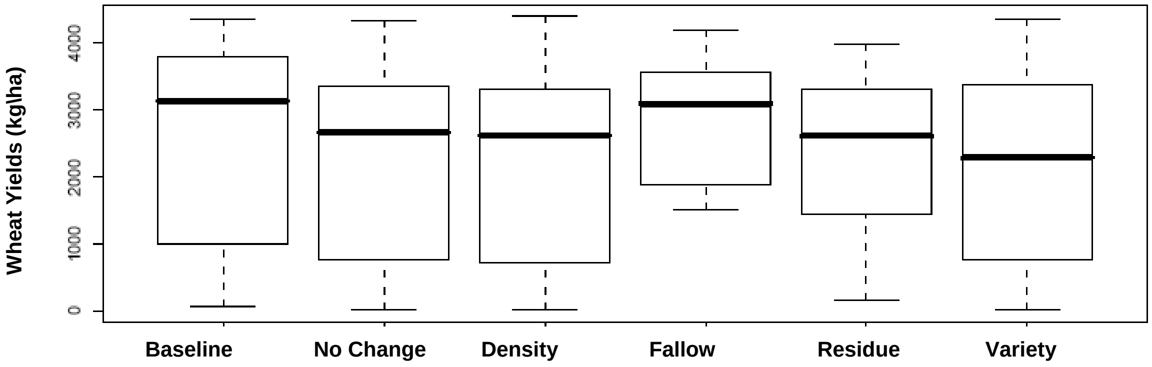


***Figure 7**: Birchip(Farm 4) – Simulated wheat yields (kg/ha) for a mixed cropping/grazing farming system under current climate conditions (baseline- 1957 to 2006) compared with simulated wheat yields under a 'high' range climate change scenario from the MARK3 climate model projections in 2030.*

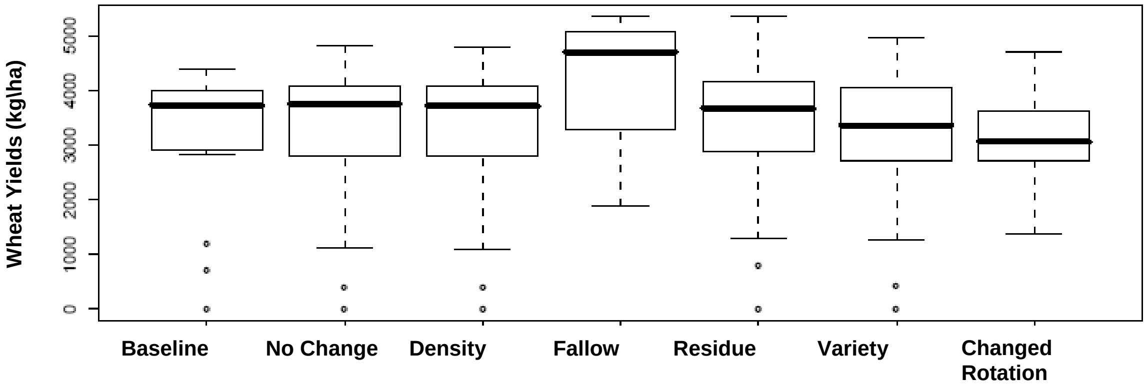


***Figure 8**: Birchip (Farm 5)– Simulated wheat yields (kg/ha) for a mixed crop farming system under current climate conditions (baseline- 1957 to 2006) compared with simulated wheat yields under a ''mid' range climate change scenario from the HADCM3.1 climate model projections in 2030 .*

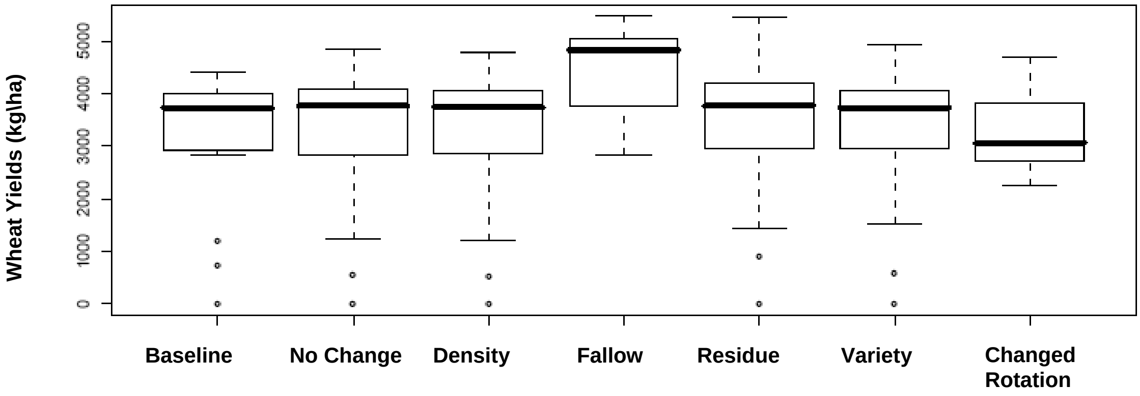


***Figure 9**: Birchip(Farm 5) – Simulated wheat yields (kg/ha) for a mixed crop farming system under current climate conditions (baseline- 1957 to 2006) compared with simulated wheat yields under a 'mid' range climate change scenario from the MARK3 climate model projections in 2030.*

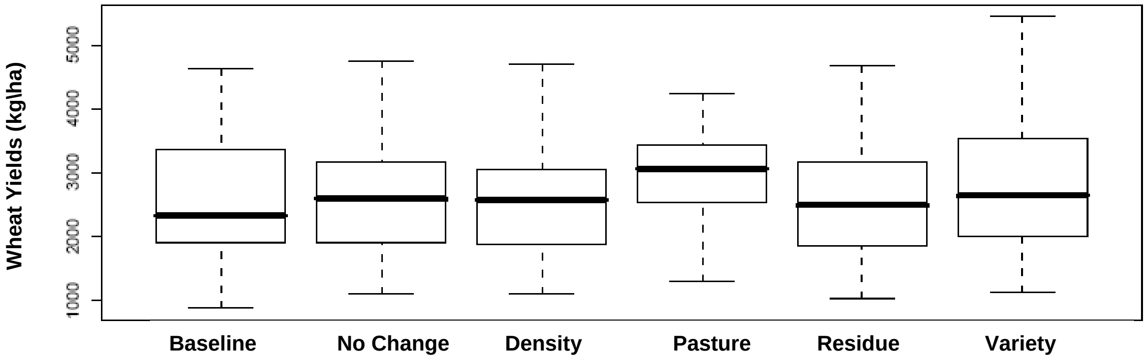


***Figure 10**: Mingenew (Farm 1) – Simulated wheat yields (kg/ha) for a mixed cropping/pasture system under current climate conditions (baseline- 1957 to 2006) compared with simulated wheat yields under a 'mid' range climate change scenario from the MARK3 climate model projections in 2030.*

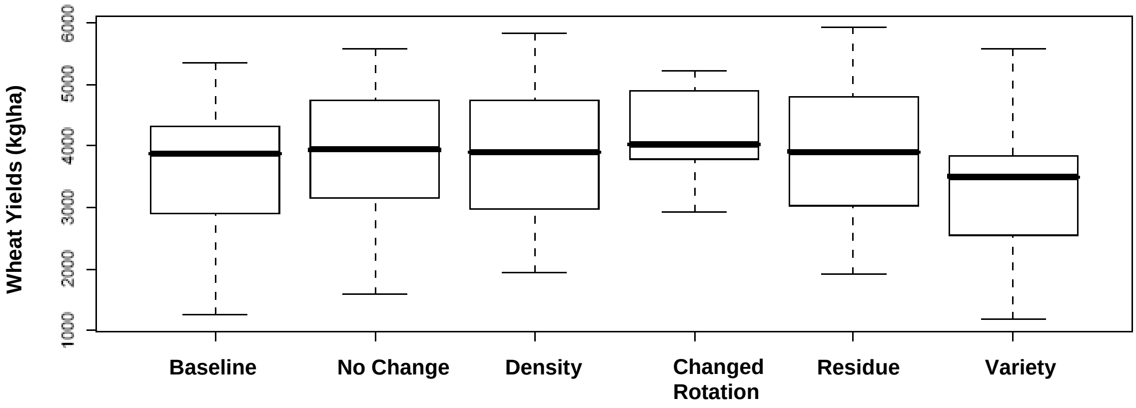


***Figure 11**: Mingenew (Farm 2) – Simulated wheat yields (kg/ha) for a mixed cropping system under current climate conditions (baseline- 1957 to 2006) compared with simulated wheat yields under a 'mid' range climate change scenario from the MARK3 climate model projections in 2030.*

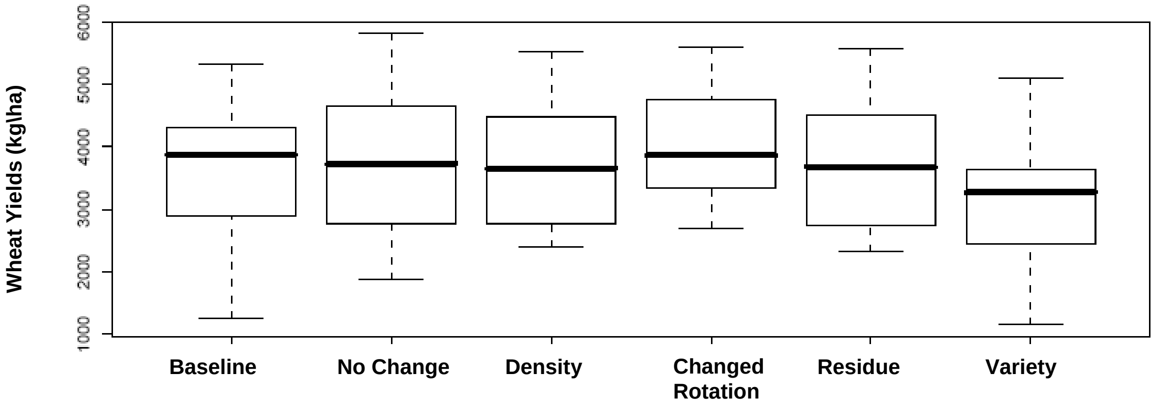


***Figure 12**: Mingenew (Farm 3) – Simulated wheat yields (kg/ha) for a mixed cropping system under current climate conditions (baseline- 1957 to 2006) compared with simulated wheat yields under a 'mid' range climate change scenario from the MARK3 climate model projections in 2030.*

APPENDIX C

Evaluating the value of the research: a stakeholder perspective

A formal evaluation was conducted with all the participating farmers in each of the three study regions. The aim of the questionnaire was to evaluate the value of the different research elements undertaken as part of the project and the communication of the research outcomes. The evaluation questionnaire was presented to each of the participating farmers (12 in total) after follow-up interviews had been conducted.

The questionnaire was designed to assess the extent of prior knowledge and the contribution of the project to improving knowledge, changing attitudes, skills and aspirations based on well established KASA principles. In the majority of cases the questions used a simple rating system to capture answers. For some questions, more open-ended answers were required in order to capture changes in attitudes, knowledge or aspirations.

In addition to the participant evaluation, a wider group of farmers and industry stakeholders were requested to evaluate the information generated as part of the research project by listening to a 20 minute presentation. Presentations were conducted in Bendigo and Birchip and evaluation forms were collected from a total of 45 respondents.

The following is an analysis of the information gathered as part of the participant evaluation and responses to the communication and extension exercise.

Climate trends and climate change

The first section of the project participant evaluation posed a series of questions to determine whether participants considered they had personally experienced changes in ‘average’ climate conditions, what some of those changes had been, how they had adapted to them and how successful the adaptation measures had been.

All the respondents considered themselves to have experienced a change in the ‘average’ climate (temperature, rainfall patterns, frequency and intensity of cyclones, etc) during the past 10 years. All the respondents identified changes in frost frequency and severity as the most marked change followed by recent droughts, warmer summer months, smaller individual rainfall events and more extreme heat and rainfall-related events. When asked how much of the change could be attributed to human induced climate change, as opposed to natural variation, 88% of the respondents indicated that a “*moderate*” or greater proportion of the change could be attributed to global warming, with 50% of respondents indicating a “*substantial*” and “*significant*” amount could be attributed to global warming. Only 12% of the respondents suggested that “*none*” of the change could be attributed to global warming.

The majority (88%) of the respondents indicated that they had already made changes to their management practices to offset the changes in ‘average’ climate conditions. Many of these respondents had altered planting dates, changed cropping varieties and crops, reduced soil disturbance and altered inputs such as nitrogen and phosphorus based on experimentation, consultants' advice or discussions with other practitioners. Some had indicated that in response to the changing climate conditions they had increased their off-farm investments or changed the mix of their enterprise (i.e. the balance between cropping and livestock). The majority (75%) of the respondents indicate that they had experienced "*moderate*" or greater success with these changes, with 25% indicating "*substantial*" successes (Fig. 1).

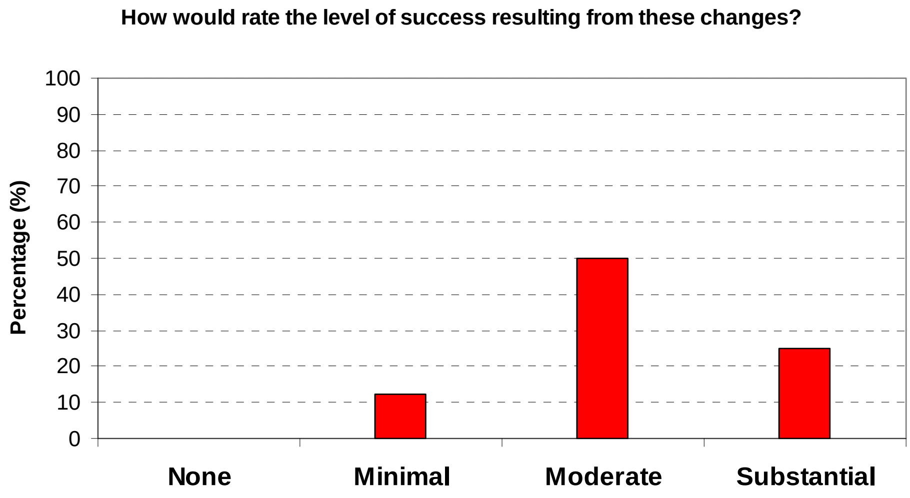


Figure 1: *The extent to which farmers determine the success of the adaptation measures they have implemented.*

When asked to what extent the research undertaken in this project had contributed to the participant's understanding of climate trends in the region, the majority (88%) of respondents indicated that the contribution had been "*substantial*" or greater, with 38% stating that the contribution had been "*significant*" and 12% responding that the contribution had been "*extensive*" (Fig. 2). Only 12% responded that the project had contributed in a "*minimal*" way (Fig. 2).

The same question was posed as part of the presentation evaluations. The majority (79%) of the participants stated that the presentation had made a moderate or greater contribution to their understanding. However, the results showed a shift towards the "*moderate*" contribution (i.e. 46% considered that the presentation had made a "*moderate*" contribution, 24% considered the presentation to have made a "*substantial*" contribution and 9% a "*significant*" contribution) (Fig. 2). The results would thus suggest that the presentation was a less effective means of promoting an understanding of regional climatic trends than the small group or intensive one-on-one interactions with the project participants.

Both the project participants and presentation attendees were asked to measure the importance of understanding the climate trends in effectively managing their farms (Fig. 3). The responses differed markedly between the project and presentation groups, with all of the project participants considering that understanding climate trends was of moderate or greater importance for managing their farms, with 62% stating that this had "*significant*" or "*extensive*" value. In contrast, 80% of the presentation attendees stated that climate trends were of "*moderate*" or greater importance with 17% stating that this had "*significant*" or "*extensive*" value (Fig. 3).

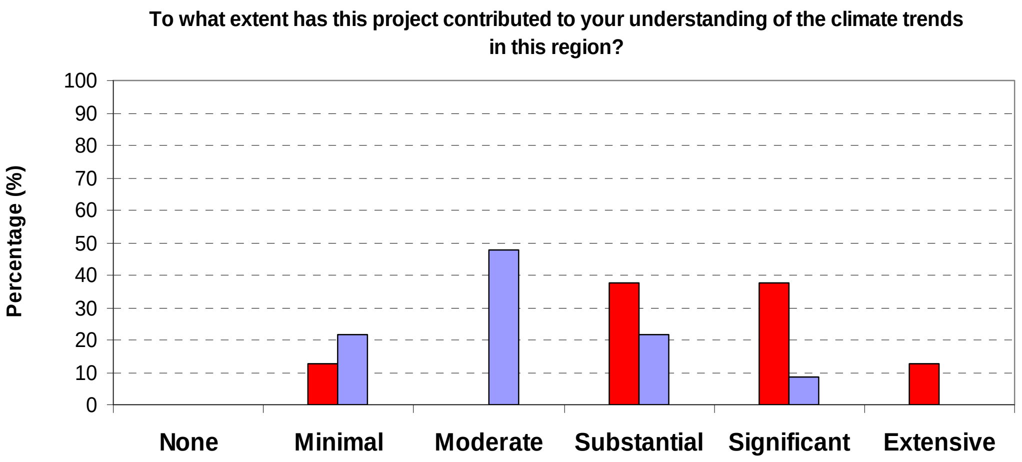


Figure 2*:* *The extent to which project participants (red) and presentation attendees (blue) valued the contribution the project made to improve the understanding of existing trends.*

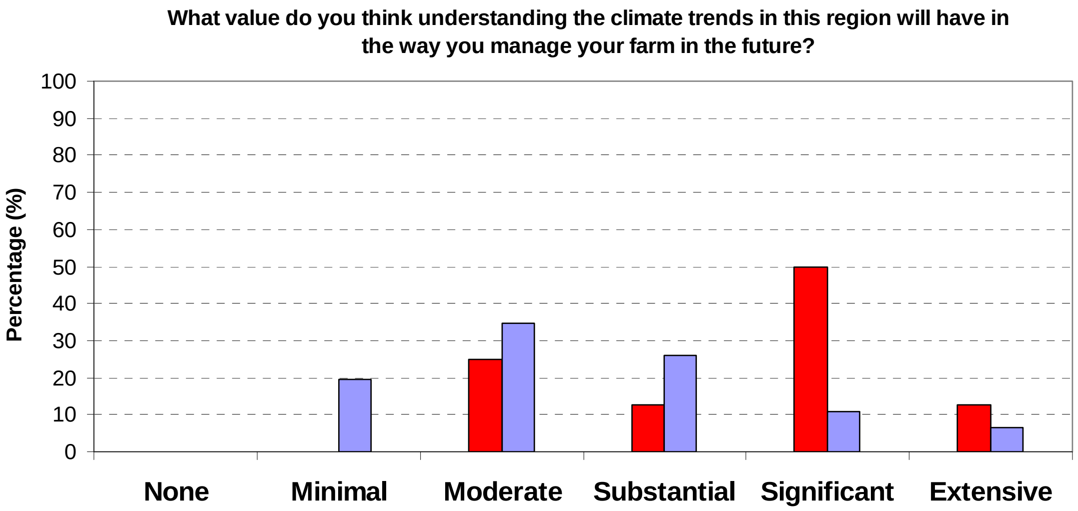


Figure 3*:* *The extent to which project participants (red) and presentation attendees (blue) valued understanding trends as a part of effective farm management.*

The project participants were asked if they would use the climate trend information generated as part of the project and all respondents indicated they would. Table 1 includes a range of options identified by project participants identifying how they might include climate trend information to vary current management practices.

***Table 1**: Examples of how project participants currently utilise climate trends to vary on-farm management*

Options to include climate trend information to vary management
• Plant later maturing crops or undertake later plantings.
• Continue to manage frost.
• Change crop/livestock mix and fertiliser inputs to account for drier trend.
• Change the proportion of the farm cropped and reduce upfront inputs.
• Reconsider further land acquisition at current prices.
• Continue to experiment with on-going incremental/opportunistic changes.

The project participants and presentation attendees were asked to measure the extent to which the research/presentation had contributed to their understanding of likely future climate conditions, and the value this understanding would have in the future management of their farm. The project participants placed a higher value on the research contribution with 50% indicating the research had provided "*substantial*" or greater value (Fig. 4) compared with 30% of presentation attendees. The presentation attendees placed less value on the contribution to their understanding with more of them indicating only "*moderate*" or "*minimal*" additional understanding (Fig. 4) when compared with the project participant group.

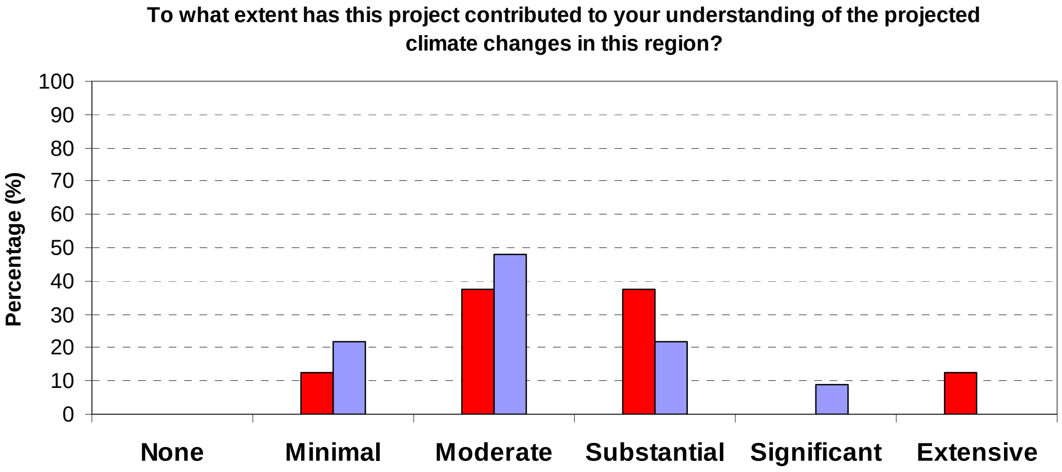


***Figure 4**: The extent to which project participants (red) and presentation attendees (blue) valued the contribution of the research/presentation in furthering their understanding of projected climate change.*

Similarly the presentation attendees placed less value on the understanding of climate projections as an effective way of managing their farm in the future (Fig. 5). All project participants responded that understanding the projections would have "*moderate*" or greater value in future farm management with 72% stating that the projections would have *"significant"* or greater value. In contrast, 82% of the presentation attendees viewed this information as having *"moderate"* or greater value with only 22% indication *"significant"* or greater value.

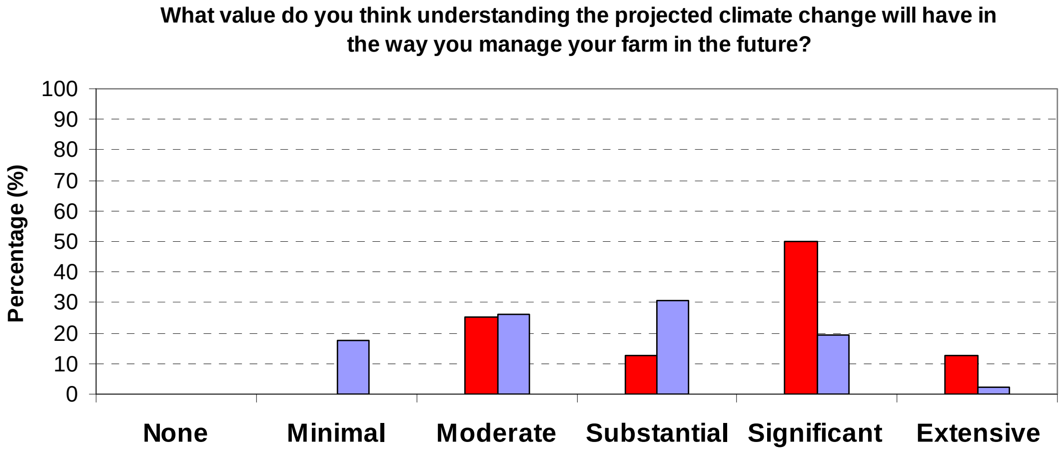


***Figure** 5: The extent to which project participants (red) and presentation attendees (blue) valued understanding future climate projections as a way of effectively managing their farm in the future.*

All the participants considered that understanding both climate trends and climate projections had some value in the future management of their farm. Many of the participants considered response activities needed to be planned immediately and that an ongoing process would be required to respond to climate changes. These decisions are likely to rely on continued research and development to provide information to enable an increase in personal knowledge and informed decision-making.

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