New Rural Industries for Future Climates
New Rural Industries for Future Climates

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Abbreviations

<table>
<thead>
<tr>
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<tr>
<td>BoM</td>
<td>Bureau of Meteorology</td>
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<tr>
<td>CSIRO Mark 3</td>
<td>Climate model produced by the CSIRO, Australia</td>
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<td>GFDL</td>
<td>Climate model produced by the Geophysical Fluid Dynamics Laboratory (New Jersey)</td>
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<td>DAFWA</td>
<td>Department of Agriculture and Food Western Australia</td>
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<td>DPI</td>
<td>Department of Primary Industries</td>
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<tr>
<td>ECHAM</td>
<td>Global climate model (Max Planck Institute for Meteorology, Germany)</td>
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<tr>
<td>GHG</td>
<td>Greenhouse gases</td>
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<td>IPCC</td>
<td>Intergovernmental Panel on Climate Change</td>
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<tr>
<td>RIRDC</td>
<td>Rural Industries Research and Development Corporation</td>
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<tr>
<td>USDA</td>
<td>United States of America Department of Agriculture</td>
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Foreword

Climate change has the potential to substantially alter the mix of agricultural industries across many regions of Australia. It will threaten the viability of some existing agricultural industries and create opportunities for new rural industries that are better adapted to future climates. The importance of this report is that it brings together climate projections with an assessment of the vulnerability of existing agricultural industries, and suggests possible production opportunities. A number of opportunities for new rural industries are described, the plant traits necessary for productive crops in these conditions are discussed, and new rural industries options that fit these requirements are suggested.

The research has a strong focus on plant industries. RIRDC recognises the need and opportunity for adaptation and new rural industries in the animal sectors and this will be a focus of future research.

In southern Australia climate change will result in warmer and drier environments that will require more resilient irrigated industries and industries suited to such conditions. Northern Australia may be less impacted by climate change, but there is a need to efficiently utilise any development of new irrigation resources.

Ongoing research is required to underpin the progress of these industries in adapting the agronomic systems required and developing markets and supply chains.

The Rural Industries Research and Development Corporation invests in new and emerging rural industries on behalf of government and industry stakeholders. New rural industries are a vital component of adaptation of Australian agriculture to climate change. They can provide diversity and resilience to adapt to future climates that many existing industries appear not to offer. In addition to providing guidance for the allocation of research funding, this report also provides direction to those working to establish new rural industries.

This report, an addition to RIRDC’s diverse range of over 1900 research publications, forms part of our New Plant Products R&D program, which aims to facilitate the development of new rural industries based on plants or plant products that have commercial potential for Australia.

Most of our publications are available for viewing, downloading or purchasing online through our website www.rirdc.gov.au. Purchases can also be made by phoning 1300 634 313.

Peter O’Brien
Managing Director
Rural Industries Research and Development Corporation
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What the report is about

The New Rural Industries for Future Climates project has considered the vulnerability of existing agricultural industries to, and the role of new rural industries in, the expected future climates across Australia taking into account climate change projections over the next 60 years. Six broad Australian agricultural regions were examined. In this report a number of new opportunities for agricultural production in future climates are described, the traits required for well-adapted industries to take advantage of these opportunities are discussed, and new rural industries that fit these requirements are suggested.

Recent climatic changes and future projections indicate warmer and drier conditions over southern Australia. Broadacre irrigated industries, such as dairy and rice, have been heavily impacted by reduced irrigation water availability and increased water price over the last 10 years, with water transferred to higher value uses. High value irrigated industries and a range of resilient irrigated industries, that allow producers to respond to water availability and price without jeopardising future production, are required. Rainfed industries are more resilient to climate variability and change; however, the benefits of adaptation options within these industries occur with moderate warming (up to 2°C). With warming of more than 2°C, little additional benefit of adaptation within industries is observed so increased farm diversification and transformation of land uses will be required to adapt to these climates. High greenhouse gas emission trajectories (i.e. the Intergovernmental Panel on Climate Change fossil fuel intensive (A1FI) scenario) estimate that 2°C warming may be expected by 2050. In the lower rainfall regions, such as the Murray–Darling basin and the marginal cropping fringe of southern Australia, a range of industries suited to drier and hotter conditions will be required.

In northern Australia, the predicted impact of climate change on rainfall is less clear with no definite signal for increasing or reduced rainfall. New industry opportunities are available to take advantage of existing, and possibly new, irrigation schemes.

Background

Increasing emissions of carbon dioxide and other greenhouse gases are altering the composition of the atmosphere. It is very likely that most of the global warming since the mid-20th century is due to increases in greenhouse gases from human activities. The Intergovernmental Panel on Climate Change (IPCC) concluded that the agriculture sector is particularly vulnerable to climate changes, with potential negative impacts on the amount of produce, quality of produce, reliability of production and integrity of the natural resource base on which agriculture depends. The current mix of agricultural industries within Australia has developed over the past two centuries in response to changing export market demands and continually evolving technology, under climatic patterns characterised by high variability but relatively steady climate trends. Projected climate change, global development and
wealth creation have the potential to dramatically alter this industry mix both spatially and temporally. These changes to farming environments and business operating conditions will provide many threats and some opportunities for Australia’s farmers. In order to survive and thrive under these changing conditions, farmers will require a greater diversity of agricultural enterprises encompassing an increased range of climatic suitabilities.

**Aims/objectives**

This project explored the potential for new rural industries and enterprises to fill land-use opportunities in areas where current agricultural industries may be strongly challenged by future climates. The specific aims were to identify the regions and industries where climate change will alter the current mix of agricultural industries, determine the plant traits required for successful new rural industries in future climates, and suggest new rural industries that meet these criteria.

**Methods used**

Six broad agricultural regions were identified that encompassed a range of climates and agricultural production systems across Australia: northern Australia, north-eastern Australia, Murray–Darling basin, marginal cropping fringe of southern Australia, southern Australia high rainfall and western Australia high rainfall. A review of the literature on the impacts and adaptation options for mainstream agricultural industries was conducted, and this information was combined with recent climate and future climate projections to determine the vulnerability of agricultural industries in each of the regions. For industries and regions identified as under particular threat from climate change, a suite of plant traits necessary for adaptation to new production opportunities was identified. Industry options suited to these regions were identified through a project workshop, searching the national and international literature, and using a plant modelling approach.

**Results/key findings**

Climate change projections for Australia indicate higher temperatures and evaportranspiration demand, changes to rainfall patterns, increased probabilities of extreme climatic events, and higher atmospheric CO₂ concentrations. Broadacre irrigated industries appear to be particularly challenged in future climates due to reduced water availability, because water is traded to higher value irrigated industries and land is converted to dryland agriculture.

New rural industries adapted to the warmer and drier future climates expected in southern Australia will require plant traits that increase water-use efficiency, heat tolerance, frost tolerance, and have lower chilling requirements. Three specific production opportunities were identified:

- High value irrigated crops – that rely on adequate supplies of high quality irrigation water to ensure production and product quality. Production systems that require a consistently large amount of good quality irrigation water will need to produce a high value product to ensure their financial sustainability as the amount of irrigation water decreases. Crops in this category include traditional horticultural industries such as pomefruit and citrus.

- Resilient irrigated crops – that have lower water requirements and/or can tolerate periods when irrigation cannot be supplied (due to low availability or high price), then rapidly respond when irrigation water becomes available. Resilience to low water availability can be achieved with drought tolerant perennial species, or annual plant based systems where the crop is planted only when water will be available. Salinity-tolerant crops are also considered here. Examples of resilient irrigated crops include: olives, jojoba, pomegranates, capers, Australian native bush foods (such as quandong, bush tomato, desert lime), cacti, dates and annual crops.

Resilient irrigated crops, such as the olive, have lower water requirements at production levels of less than 100% compared to traditional industries, such as citrus, making them better suited to the lower and more variable irrigation water availability regimes expected in future climate scenarios for southern Australia. A comparison of the water use efficiency and farm income of olive and citrus orchards was made using the irrigation allocations available in northern Victoria over the last 10 years as an indicator of future water allocation patterns. During this period irrigation allocations averaged 80%, and a 26% increase in the gross value of production per ML irrigation applied and a 15% higher gross farm income over the period for the olive compared to the citrus orchard was demonstrated. This difference is amplified with further declines in irrigation availability, for example, at 50% water allocations the gross value of production per ML irrigation applied for the olive orchard was double that of the citrus orchard. In addition, the drought tolerance of olive trees allows them to survive and resume production rapidly after a period of severe water stress, whereas citrus trees need to be heavily pruned to reduce their water use when irrigation is not available and take 2-3 years to resume full production. This drought tolerance will be an important plant trait in future production environments characterised by lower and more variable irrigation water availability.

- Dryland farming systems – with declining total amounts of irrigation water there will be a conversion to dryland agriculture. Examples of industries considered here include: mustards, crambe, quinoa, tepary bean, Australian native grass crops, industrial crops (such as guayule, lesquerella, buffalo gourd and grindelia), eucalypts for oil and extensive animal industries (goats and kangaroos).

Northern Australia is potentially less affected by climate change than the southern regions because there is no clear signal for increased or decreased rainfall. However, increased temperatures, and consequently, increased evaporation, are
predicted for this region and, together with extremely low
winter rainfall, this highlights the importance of water use
efficiency in new crops. Examples of potential new rural
industries for northern Australia include peanuts, watermelon,
pomegranate, kenaf, bitter melon, sesame, burdock and guar.

At a regional scale, increasing agrodiversity is suggested
as a means of reducing the risk associated with extreme
climatic events by having a range of crops at different
stages of their production cycle at any single point in
time. In this way an extreme climate event, such as a
heatwave or cyclone, will not affect all production from
a farm or region.

Implications for relevant stakeholders
Australian agriculture is highly vulnerable to the impacts of
climate change projected for the next century. The challenges
of the future are not necessarily the same as those of the past,
e.g. irrigated industries were established in an era of high
water availability and are not resilient to lower and more
variable irrigation water supplies. The options required to
deal with the challenge of climate change will be increasingly
complex, ranging from adaptation within existing industries
to cope with moderate climate change (up to 2°C warming),
to increased diversification, and transformation to new land
uses to adapt to progressively larger climate change.

The challenge for industry and communities is to
incorporate climate change into their planning and decision
making to account for the unavoidable impacts of climate
change. This will involve thinking about the new rural
industry opportunities identified in this report.

The challenge for policy makers is to aid the transition
from existing to new rural industries. This may involve
the establishment of new infrastructure to support new rural
industries, such as to service irrigation, transport or processing
needs. It will also require sustained investment in new rural
industries research and development, to refine agronomic and
industrial processes for Australian conditions. The benefit of
moving from a traditional to a resilient irrigated horticultural
crop was estimated to be a 26% improvement in water use
efficiency in the case of olives compared to citrus, using the
last 10 years of water allocations in northern Victoria as an
indicator of lower and more variable water availability in
future climates. Further benefits from improved drought
survival and more rapid resumption of production following
water stress are expected. Productivity improvements such
as this are important, but research must also focus on
opportunities that will provide a transformational change
in agriculture to cope with warmer and drier conditions in
southern Australia. Plants such as cacti offer the potential
of an order of magnitude increase in water use efficiency. In
planning for the risks associated with the higher frequency of
extreme events predicted in future climates, such as droughts,
heatwaves and intense tropical cyclone, an important strategy
will be to increase the diversity of agricultural industries in a
region.

Recommendations
This project provides the first step in identifying new industry
opportunities for Australia taking into account projections
for future climate. The recommendation of this report is
that the development of new rural industries is an essential
component of the adaptation of Australian agriculture to
meet the challenge of climate change. New rural industries
provide the potential for a transformational shift in adaptation
to future climates that existing industries appear not to offer.

There is much research to be done to evaluate the economics
of industry options and develop agronomic techniques for
Australian conditions. The PLANTGRO modelling approach
used in this project demonstrated the limited capability
to predict performance of new crops. Significant research
and development challenges exist for the establishment of
new rural industries as viable commercial farming systems
so greater investment in R&D for new rural industries is
warranted.
Introduction

Increasing emissions of carbon dioxide (CO₂) and other greenhouse gases (GHG) are altering the composition of the atmosphere. It is very likely that most of the global warming since the mid-20th century is due to increases in GHG from human activities (IPCC 2007). Eleven of the last twelve years (1995-2006) rank among the 12 warmest years in the instrumental record of global surface temperature (since 1850). Regardless of the actions that we take today, some degree of global warming is inevitable so adaptation will be an essential risk management strategy (IPCC 2007). Expected shifts in annual average temperature between now and 2030 will be in the order 0.2 to 1.3°C in many of the Australian agricultural regions. By 2050, the projected increase in annual average temperature will be in the range of 0.4 to 2.6°C (CSIRO and BoM 2007). This range of warming values exists because of the range of uncertainty in GHG projected to be emitted in the future, uncertainty in the sensitivity of the climate system to a given increase in GHG, and differences between climate models in spatial patterns of warming across the continent (IPCC 2007). The IPCC concluded that the agricultural sector is particularly vulnerable to climate change, with potential negative impacts on the amount of produce, quality of produce, reliability of production and integrity of the natural resource base on which agriculture depends. This vulnerability requires high levels of adaptive responses (Howden et al. 2007).

The current mix of agricultural industries within Australia has developed over the past two centuries in response to changing export market demands and continually evolving technology, under climatic patterns characterised by high variability but relatively steady climate trends. Projected climate change, global development and wealth creation have the potential to dramatically alter this industry mix both spatially and temporally in the next 30 years. These changes to farming environments and business operating conditions will provide many threats and some opportunities for Australia’s farmers. In order to survive and thrive under these changing conditions, farmers will require a greater diversity of agricultural enterprises adapted to a wider range of climates.

The current RIRDC New Rural Industries portfolio has a responsibility to develop new rural industries/enterprises for changing market demands and land use availability. The projected changes in the climates of Australia’s agricultural regions may threaten the viability of some existing industries within particular regions and create opportunities for new enterprises. These impacts may lead land managers to explore alternative rural industries/enterprises in order to maintain farm cash flow. This project explores the opportunities for new rural industries and enterprises to provide alternative land uses in areas where current agricultural industries may be strongly challenged by future climates.
Objectives

The objectives of this project were to:

• Identify regions in both southern and northern Australia where climate change will mean that the current mix of agricultural enterprises will no longer be viable due to lower rainfall, higher temperatures or changed rainfall/temperature distributions.

• Identify a subset of regions where there are no obvious other mainstream current enterprise (crop or livestock) options for landholders or where new rural industries are necessary for maintaining the resilience of the farming system.

• Identify selection criteria for potential new enterprises in the selected regions in future climates, e.g. water use efficiency and heat tolerance.

• For the selected areas, identify possible new enterprise options that could be viable in these areas, together with the resource and climate requirements for these industries (crops or livestock). These new enterprises may come from:
  – the RIRDC New Crops Handbook
  – case studies
  – other international sources e.g. from countries with climates similar to projected Australian climates such as Israel and California.

• Identify the changes (e.g. practices, infrastructure, costs) that are necessary to establish these enterprises at the farm and regional levels.

• Conduct a broad cost/benefit analysis and feasibility of change to the most feasible options.

• Prepare a preliminary business case for greater investment in research and development for new rural industries in the face of changing climates if this is warranted as a result of the above analysis.

Methodology

Regions

Six broad agricultural regions were examined, encompassing a range of climates and agricultural production systems across Australia. As the regions were large, two sites within each region were selected for the analysis of climate change projections. These regions and sites are:

• Northern Australia - Katherine (Northern Territory) and Kununurra (Western Australia).

• North-eastern Australia - Mackay (Queensland) and Emerald (Queensland).

• Murray–Darling Basin - Goondiwindi (Queensland) and Kyabram (Victoria).

• Marginal cropping fringe of southern Australia - Birchip (Victoria) and Merredin (Western Australia).

• Southern Australia high rainfall - Ellinbank (Victoria) and Hamilton (Victoria).

• South-west Australia high rainfall - Albany (Western Australia) and Bunbury (Western Australia).

The location of each of the sites is shown in Figure 1.

![Figure 1. Map of Australia showing the location of the towns for which climate data is presented in this report.](image-url)
Climate data and climate change projections

Four scenarios were developed to quantify the historical, recent, and projected climate for each of the six regions across Australia. A detailed analysis of the climate changes at two sites in each region was prepared, which included a range of climate statistics with relevance to agricultural industries, such as seasonal rainfall and temperature, frequency of hot and cold days, and projected changes in extreme events. The four climate scenarios were:

- Baseline climate – based on observed climate data from 1/1/1961 to 31/12/1990. The period of 1961 to 1990 was used because this is the baseline climate used in climate change science. Baseline and recent (see point 2 below) climate data were obtained from the Bureau of Meteorology SILO database (http://www.longpaddock.qld.gov.au/silo/, Jeffery et al. 2001).

- Recent climate – based on observed climate data from 1/1/1998 to 31/12/2007.

- 2030 future climate – based on regional climate projections for temperature and rainfall change under a high GHG emission scenario (i.e. the IPCC A1FI emission scenario) in 2030. This scenario reflected a global temperature increase of approximately 1°C. Further details of how the future climate scenarios were constructed are provided below.

- 2070 future climate – based on regional climate projections for temperature and rainfall change under a high GHG emission scenario (i.e. the IPCC A1FI emission scenario) in 2070. This scenario reflected a global temperature increase of approximately 4°C. Further details of how the future climate scenarios were constructed are provided below.

The future climate scenarios were constructed for each site by combining historical climate data with projections for climate change from global circulation models, following the method outlined in Cullen et al. (2009). For the 2030 future climate scenario, projections for the A1FI emission scenario with High climate sensitivity (IPCC 2007) in 2030 were used. For the 2070 future climate scenario, the same IPCC emission scenario was used but with output for 2070. The A1FI scenario was developed by the IPCC and is based on assumptions of rapid economic growth throughout the next century with the global population peaking at 9 billion in 2050 then gradually declining, and fossil fuels remaining the major source of energy. The A1FI scenario has the highest rate of production of GHG emissions of the suite of IPCC scenarios (IPCC 2007).

There is uncertainty in the projections for future temperature and, in particular, rainfall changes, so the range in projections from three climate models is presented for each region. The climate models used were the CSIRO Mark 3, GFDL and ECHAM models. The global climate model projections were obtained on a seasonal time-step from the OzClim database (www.csiro.au/ozclim) in March 2009. These results are presented for each region in Tables 1, 3, 5, 7, 9 and 11.

The seasonal average rainfall, minimum and maximum temperature patterns for the four climate scenarios are shown for each site in Figures 10-15. In these Figures the climate projections for the 2030 and 2070 scenarios were taken from a single global circulation model, that is the CSIRO Mark 3 model. Projections from a single model were used here to ensure internal consistency of the scenarios (CSIRO and BoM 2007).

While the above approach captured changes to the mean climate it did not account for projected increases in extreme climate events, defined as ‘an event of such intensity that it is rare at a particular time of year or place’ (Alexander & Arblaster 2009), such as heat waves and high intensity rainfall events. A review of the literature was used to describe changes in extreme climatic events for each of the regions, principally based on the work of CSIRO and BoM (2007) and Alexander & Arblaster (2009). Projected changes in the frequency and intensity of extreme climatic events for each region are presented in Tables 1, 3, 5, 7, 9 and 11.

Approaches to identifying new industry opportunities

A literature review was conducted to identify the impacts of climate change on mainstream agricultural industries. For each region, the historical climate and future climate projections were combined to characterise the threats to agricultural production in each region. Regions under particular threat from climate change were identified and the plant traits required for suitable industries were determined. New industry opportunities for these regions were identified from a project workshop (4th June 2009) and by searching the national and international literature.

A modelling approach, using the PLANTGRO software (Hackett 1991), was also used to indicate new crop opportunities in future climates. The strengths and weaknesses of this approach are outlined in the modelling chapter.
Vulnerability of existing agricultural industries to climate change

Introduction

Climate change projections for Australia include higher temperatures and evapotranspiration demand, changes to rainfall patterns, higher atmospheric CO₂ concentrations, and increased probabilities of extreme climatic events (Garnaut 2008). The impacts of projected climate changes on the productivity and sustainability of the major agricultural industries in Australia, such as dryland wheat cropping systems (Crimp et al. 2008) and grazing systems (Howden et al. 2008), have been assessed using agricultural systems models and expert opinion over the last 20 years. Garnaut (2008) concluded that Australian agricultural industries were highly vulnerable to the impacts of warming and changes in rainfall patterns, with broadacre irrigated agriculture (grains, dairy and sheep) being ranked as ‘very high’ vulnerability, broadacre dryland industries as ‘high’ vulnerability, and high value irrigated industries (horticulture/viticulture) as ‘moderate’ vulnerability. However, there will also be regional variation in the vulnerability of agricultural industries across Australia due to differences in climate change projections.

The aim of this literature review is to summarise the climate change impact assessments and adaptation options for mainstream agricultural industries in Australia with a view to identifying opportunities for new crops in regions where the current mix of agricultural industries is under threat from climate change. The focus of this review is on the Murray-Darling basin, marginal cropping fringe of southern Australia, southern Australia high rainfall and south-west Australia high rainfall regions, north-eastern Australia and northern Australia identified in the project methodology.

Irrigated agriculture

Enterprises heavily dependent on irrigation water are particularly sensitive to climate change because the relative impact of reduced rainfall and increased temperature is amplified for the flow of water into rivers, and therefore irrigation water availability (by approximately a 3:1 ratio, Jones et al. 2006). The declines in production from irrigated agriculture are predicted to be larger and to occur more rapidly than from dryland agriculture. Garnaut (2008) estimated that without climate change mitigation, the value of irrigated agricultural production in the Murray–Darling basin would decline by 12% in 2030, 49% in 2050 and 92% in 2100. Reductions in production will occur sooner under the worst case future climate scenario than under more moderate climate changes, but the adoption of climate change stabilisation policies also have the capacity to substantially mitigate the declines in irrigated agricultural production (Garnaut 2008).

Under warmer and drier climate change scenarios, the mix of irrigated industries is also predicted to change (Quiggin et al. 2008), with reductions in dairy pasture, rice and cotton,
and small increases in high value crops such as viticulture and vegetables.

Irrigated broadacre cropping and grazing systems will be greatly affected by the reduced availability of water. A range of adaptive responses to lower irrigation water availability in broadacre irrigated cropping systems was modelled by Connor et al. (2008). These adaptations, including deficit irrigation, temporary fallowing of some areas, permanently reducing irrigated area, and changing the mix of crops, suggest that relatively low cost adaptation strategies are available for moderate reductions in water availability. However, in more severe climate change scenarios, greater costs are estimated to occur and a reduction in total irrigated area irrigated is predicted (Connor et al. 2008). In these conditions, a shift from perennial to annual crops is likely as these can be managed more profitably when water allocations are very low.

Irrigated dairy will be dramatically affected by reduced irrigation availability, given that in some areas of the southern Murray–Darling basin such as the Goulburn-Broken region, more than 60% of irrigation water is used by the dairy industry (Robertson et al. 2007). The recent drought in the region has already had a large impact on water diversions for dairy. For example, the 2007/2008 water allocations for Murray and Goulburn closed at 43% and 57%, respectively, of allocations for the year (Victorian DPI 2008). Irrigation system technologies such as automation, which improves water efficiency and reduces labour, and forage management, will be important for the future of the dairy industry. Recurrent droughts have already forced farmers to look at alternative measures to fill the feed gaps brought about by insufficient irrigation water allocations to sustain the growth of perennial pastures through summer. Purchasing more feed from off-farm is one option, although it costs more than home-grown feed (Chapman et al. 2008). Alternative strategies being investigated to fill the feed gap involve changes in farm and irrigation system management of pastures. Strategies to alter the pasture species mix include using more annuals which require irrigation water only at the start (autumn) and end (mid-late spring) of their growing season, and planting high-producing summer crops such as maize which can be conserved as silage (Garcia et al. 2008). Strategies for irrigation management include use of sub-surface drip irrigation to apply limited irrigation water more precisely. However, changes in the optimum economic balance of grain, pasture and water inputs of some areas will result in their reduced suitability for irrigated dairy production (Hacker et al. 2007).

**Livestock and dryland pasture production**

The main impacts of climate change on dryland grazing systems are a reduction in livestock carrying capacity, changes in forage quality (higher carbohydrates, lower nitrogen content, species composition; Howden et al. 2008; Scholes & Howden 2003), increased heat stress on animals, and changed distributions of pests, diseases and weeds (Harle et al. 2007; Howden et al. 2008). The modelling of climate change impacts on pasture production in southern Australia indicates similar results to those described for crop systems. Existing systems are resilient to 1°C warming and 10% rainfall decline, but annual production is expected to decline when rainfall decreases by more than 10% (Harle et al. 2007; Howden et al. 2008; Cullen et al. 2008). By 2070, annual pasture production in the high rainfall zone of southern Australia is predicted to decline by 15-25% (Cullen et al. 2008). As a consequence, livestock carrying capacity in South Australia could be reduced by up to 30% (McKeon et al. 2008; Garnaut 2008). By contrast, in northern Australia, pastures dominated by C₄ species are predicted to increase in production because of higher summer growth rates and an extended growing season (Cullen et al. 2008).

**Wheat**

The impacts of climate change on dryland wheat production are dependent on the wheat-growing region, degree of climatic change projected, and atmospheric CO₂ concentration. In a 2030 climate scenario, small increases (from 1-15%) in wheat yields are expected across the Australian wheat growing regions where existing technologies (sowing times and cultivars) are employed to adapt the system to the changed climate (Crimp et al. 2008). The improved radiation and water use efficiency observed under elevated atmospheric CO₂ concentrations (‘CO₂ fertilisation’), is an important component of this elevated production in future scenarios. However, by the end of this century gains from CO₂ fertilisation will be counter-acted by warmer temperatures and reduced rainfall, leading to a decline in annual wheat production of 21-24% in the low rainfall wheat zone. Reductions in wheat yield of a similar magnitude were modelled at Birchip in a 2070 climate scenario by Anwar et al. (2007). Under the worst case scenario (hot and dry extreme), yields were predicted to decline by 82% at Minnipa and 100% at Birchip (Crimp et al. 2008). In addition to climate change impacts on wheat yield, grain quality will also likely be affected. Grain protein content is predicted to decline under future climate and elevated atmospheric CO₂ concentration, requiring an additional 40-220 kg N/ha/year to be applied (Crimp et al. 2008). The dough making quality of the grain may also be reduced by increased heat shock (Crimp et al. 2008). The limited options for alternate break crops in wheat rotations are a particular issue, as crops like canola are more vulnerable to drought than wheat in low rainfall environments (Laing et al. 2009).
Some of the adaptation strategies for dryland grazing systems include altering livestock system management (stocking rate and rotation, crop/livestock mix, timing of mating, supplementation and weaning) according to seasonal climate forecasts, selection of sown pastures, forage crops and animal lines better adapted to higher temperatures and water constraints, revision of fertiliser management through sown legumes and phosphorus fertiliser and provision of urea and phosphates directly to stock via reticulation, development of software to assist proactive decision making at the on-farm scale, and incorporation of biological, chemical and mechanical methods for pest, disease and weed control (Hacker et al. 2007; Howden et al. 2008).

In the higher rainfall grazing areas such as southern Victoria, increasing competition for land from dryland cereal cropping is likely to occur (Harle et al. 2007).

Horticulture

Within the horticultural industries the main issues associated with climate change are likely to be changes in the suitability of regions for existing crops and cultivars, possible changes in the distribution of pests, diseases and weeds, downgrading of product quality (e.g. from sunburn), and increased irrigation water demand (Deuter 2008). Climatic thresholds are not well defined for many horticultural crops, particularly vegetables, so a quantitative assessment of the impacts of future climate scenarios on horticultural crops is not available (Deuter 2008). Research in California found that winter warming reduced the yield of crops that had a high requirement for winter chilling (cherry and almond), but that no crops benefited from warming (Lobell et al. 2009).

Adaptation strategies for horticulture include investigating opportunities for new crops in existing areas, i.e. industries with more drought tolerance and reduced or more opportunistic irrigation requirements such as olives (Connor 2004).

Viticulture

Increasing temperatures and heatwaves associated with climate change are the main concern for viticulture (Anderson et al. 2008). Higher temperature can reduce product quality, and accelerate the phenological development of the plant so that grape maturity will be reached earlier. This means that harvest will occur in an earlier (hotter) month, resulting in a ‘dual-warming’ effect. Although production may increase, declining quality is expected to decrease overall profitability. Higher irrigation water requirements due to warmer temperatures and reduced rainfall, likely higher salinity in irrigation water, pests and diseases, and quality implications for wine making are also important considerations (Anderson et al. 2008). To stay within favourable temperature ranges, the industry may have to move south or to higher elevations.

Managing for extreme climate events

Most of the analyses of climate change impact on agricultural systems has focused on assessing changes to the ‘average’ climate, but has not addressed changes in the magnitude and frequency of extreme climate events such as heatwaves, frost, or cyclones. This is, in part at least, because the changes in extreme events are difficult to quantify. However, research in California has identified that changes in the frequency of extreme events are likely to be an important component of the impact of climate change, although more research is needed to quantify the net impact of extreme events since some are likely to decrease in frequency (e.g. frost) while others are likely to increase (e.g. heatwaves) (Lobell et al. 2009). For the Yolo Valley in California, Jackson et al. (2009) recommended a gradual shift from warm season horticultural crops (e.g. tomato) to hot-season crops (e.g. melon, sweet potato) to adapt to rising temperatures, and increasing agrodiversity within a farm or region to reduce exposure to extreme climatic events as an effective means of building resilient farm systems. A lack of crop diversity in a region is associated with an economic risk in terms of climatic events such as drought or heatwaves. As the establishment of diverse agricultural systems is expensive, land use planning for diversification might involve short term losses for longer term gains (Jackson et al. 2009). These principles are also relevant to Australian agriculture but further research is needed to determine the impacts of changes in the frequency and severity of extreme climatic events on regional agricultural productivity.

General conclusions

Broadacre irrigated industries are already changing in response to recent climate drivers and are expected to continue to change as reduced water availability and increased water prices result in water being allocated to higher value industries such as horticulture. Opportunities exist for small-scale high-value crops to replace more extensive irrigated agriculture such as rice and dairy pasture, particularly with lower and/or more opportunistic water requirements. An overall reduction in the area of irrigated land is also expected.

Australian rain-fed agricultural industries have developed in a highly variable climate and appear to be well-adapted to cope with climate change projections to 2030 of 1°C warming and 10% less rainfall, using existing agronomic technologies currently employed to manage climate variability. However, there are limits to the capacity of these industries to adapt to climate change. Howden et al. (2007) demonstrated that most of the benefits of adapting cropping systems to climate change occur with moderate warming (up to 2°C); with little additional benefit to adaptation observed with further warming. The benefits of adaptation within industries are further limited if warming is associated with lower rainfall, as is expected in southern Australia (Howden et al. 2007). Under a high GHG emission scenario (i.e. the IPCC A1FI scenario), the best estimate from climate models indicates...
that warming of 2°C would occur by 2050 (CSIRO and BoM 2007). With further warming, the options required for adaptation are increasingly complex, as they shift from focusing on improving management within current industries, to increasing diversification, and finally to changing the distribution of industries by transforming land use. These three phases of adaptation have increasing levels of complexity, cost and risk (Howden et al. 2007).

At the farm to regional scale, increasing the agrodiversity of production systems will provide resilience to extreme climate events by using a broader range of crops that will be at different stages of their production cycle at any point in time, thus spreading the risk of damage from climatic events such as heatwaves, storms or frost.

Native grass species are adapted to low and irregular rainfall and high temperatures, thus should be suited to future climate scenarios. There is potential to use native grasses, such as weeping grass (*Microlaena stipoides*), as dual purpose crops, i.e. to harvest for grain in good years and use as a forage source for grazing animals in poorer years.
Climate scenarios

Introduction

The current mix of agricultural industries within Australia has developed over the past two centuries in response to changing export market demands and continually evolving technology, under climatic patterns characterised by high variability but relatively steady climate trends. However, recent and projected future climatic changes have the potential to alter the mix of agricultural industries. The aim of this chapter is to quantify recent climatic changes and the projections for future climate for each of the six regions across Australia. Four climate scenarios were developed for each region based on historical (1961-1990) and recent (1998-2007) climate data, and climate change projections for 2030 and 2070 under a high GHG emission scenario (i.e. the A1FI scenario, IPCC 2000).

A detailed analysis of the climatic changes at two sites in each region was prepared showing a range of climate statistics that have relevance for agricultural industries, including seasonal rainfall and temperature, frequency of hot and cold days, and projected changes in extreme events. These climate indices were used to determine the threats to existing agricultural industries and the characteristics of new, better-adapted industries that may take their place.

Trends in mean temperature and annual rainfall across the Australian continent from 1910 to 2008, and from 1950 to 2008, are shown in Figure 2 and 3. Mean temperatures have increased by an average of 0.9°C across the continent over the last century, with almost all of the warming occurring since 1950 (Figure 2). Over the last century the warming trend across Australia has averaged 0.09°C per decade but since 1950 the trend has been 0.16°C per decade (CSIRO and BoM 2007). There is spatial variation in the warming pattern, with the maximum warming occurring in central and eastern Australia and the minimum warming/slight cooling occurring in north western Australia (Figure 2).

The trend in total annual rainfall across Australia shows increased precipitation across the north-west of the continent but declining rainfall across much of eastern and south-western Australia (Figure 3). The trends are much clearer since 1950, with the north-west of the continent increasing annual rainfall by more than 30 mm per decade while the largest drying trend has occurred in coastal eastern Australia where rainfall has declined by more than 50 mm per decade (Figure 3). The declining rainfall trends across eastern Australia since 1950 reflect a ‘wet’ decade at the beginning of the period and extremely dry conditions over the last decade (CSIRO and BoM 2007).

In south-eastern Australia most of the decline in annual rainfall since the 1950’s can be attributed to declining rainfall in autumn (Gallant et al. 2007), although spring rainfall has also declined since 2002 (and in particular during the 2006-2008 period) (Timbal 2009), leading to the 12 year, 8 month period from October 1996 to May 2009 being recognised as the driest in the 100 year record for south-eastern Australia. This decline in rainfall has been linked with changes in global circulation patterns, particularly the intensification of the subtropical ridge (Timbal 2009), suggesting that at least part of the recent low rainfall period is associated with global warming.
Figure 2. Trend in mean annual temperature change (°C/decade) across Australia for the periods (a) 1910-2008 and (b) 1950-2008.
Figure 3. Trend in total annual rainfall change (mm/decade) across Australia for the periods (a) 1910-2008 and (b) 1950-2008.
There is general agreement between the patterns of rainfall and temperature change observed since 1950 and climate change projections for Australia. Temperature projections for Australia predict warming of 0.4 to 1.8°C by 2030 and 2.2 to 5°C by 2070 under high emission scenarios (A1FI storyline, IPCC 2000), with larger increases inland compared with southern Australia (Figure 4).

There is some variation in the patterns of projected changes to minimum and maximum temperatures. In southern Australia, minimum temperatures are projected to rise more slowly than maximum temperatures, while across northern Australia, minimum temperatures are projected to rise more rapidly than maximum temperatures (CSIRO and BoM 2007). For example, across Victoria the spring minimum temperature is projected to increase 10-15% more slowly than the average temperature. These differences are related to projected changes in cloud cover associated with lower rainfall in southern Australia and increasing rainfall in northern Australia (CSIRO and BoM 2007). The slower increase in minimum temperature across southern Australia has important implications for the incidence of frost, as the decrease in the frequency of frost will be less than that predicted when using the average temperature change alone.

There is considerable variation in projected changes to rainfall patterns (Figure 5). The annual rainfall projections for 2030 range from -10 to +5% across northern Australia and from -10% to no change in southern Australia, while under 2070 high emission scenarios (A1FI) projected changes are for -30 to +20% annual rainfall in northern, central and eastern Australia, and -30 to +5% annual rainfall across southern Australia (CSIRO and BoM 2007). In southern Australia the rainfall reductions are projected to be largest in winter and spring.

Potential evapotranspiration is projected to increase by 2-4% across most of northern and eastern Australia by 2030 and by 4-12% across the continent under high emission scenarios by 2070 (Figure 6). This increase in potential evapotranspiration will further limit water availability, in addition to the declines in rainfall projected for eastern and southern Australia.

Small changes (<5%) are projected for solar radiation (Figure 7) and relative humidity (Figure 8) under the highest climate change scenario presented here (i.e. 2070, High emission scenario). Changes in solar radiation by 2030 are expected to be in the range of -2 to +1%, although there is a trend for increased radiation in southern Australia during winter and spring (CSIRO and BoM 2007). Small decreases in relative humidity are predicted across Australia, with changes by 2030 in the range of -2 to +0.5% (CSIRO and BoM 2007). Wind speed is projected to increase in coastal Queensland and central Australia (Figure 9), however it is important to note that there is large variation in wind speed projections across a range of climate models (CSIRO and BoM 2007).

![Figure 4. Best estimate (median climate model result) of annual mean temperature change from 1990 baseline climate for Low (B1), Medium (A1B) and High (A1FI) emission scenarios in 2030, 2050 and 2070 across Australia.](http://www.climatechangeinaustralia.gov.au/)
Figure 5. Best estimate (median climate model result) of annual rainfall percentage change from 1990 baseline climate for Low (B1), Medium (A1B) and High (A1FI) emission scenarios in 2030, 2050 and 2070 across Australia.

Figure 6. Best estimate (median climate model result) of annual percentage potential evapotranspiration change from 1990 baseline climate for Low (B1), Medium (A1B) and High (A1FI) emission scenarios in 2030, 2050 and 2070 across Australia.
Figure 6. Best estimate (median climate model result) of annual percentage potential evapotranspiration change from 1990 baseline climate for Low (B1), Medium (A1B) and High (A1Fi) emission scenarios in 2030, 2050 and 2070 across Australia.


Figure 7. Best estimate (median climate model result) of annual percentage solar radiation change from 1990 baseline climate for Low (B1), Medium (A1B) and High (A1Fi) emission scenarios in 2030, 2050 and 2070 across Australia.


Figure 8. Best estimate (median climate model result) of annual percentage relative humidity change from 1990 baseline climate for Low (B1), Medium (A1B) and High (A1Fi) emission scenarios in 2030, 2050 and 2070 across Australia.

Figure 9. Best estimate (median climate model result) of annual percentage wind speed change from 1990 baseline climate for Low (B1), Medium (A1B) and High (A1FI) emission scenarios in 2030, 2050 and 2070 across Australia.

Northern Australia

Climate scenarios

The northern Australia region has a tropical climate with a summer-dominant rainfall pattern. Annual average rainfall for the 1961-1990 period at Katherine and Kununurra was 1006 and 791 mm respectively, with a 27 and 20% increase in annual rainfall at these sites in the 1998-2007 period, over the baseline period (Figure 10). Climate change projections for these two sites (Table 1) indicate no clear trend for rainfall with changes of ±16% projected for 2070. In the tropical climate of northern Australia no cold days or cold nights were recorded or predicted (Table 2). With the projected warming under 2030 and 2070 climate change scenarios, the number of hot days and hot nights is expected to increase (Table 2).

Together with the changes in average climate outlined, changes in the intensity and frequency of extreme events are predicted with more heatwaves and extreme rainfall events, and an increase in the proportion of intense cyclones (Table 1).

Table 1. Summary of the range of changes in mean temperature and rainfall for the northern Australia region based on projections for the high emission scenario (A1FI) from the CSIRO Mark 3, GFDL and ECHAM climate models, and projected trends in the frequency and severity of extreme events

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Temperature change</th>
<th>Rainfall change</th>
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<tbody>
<tr>
<td>2030</td>
<td>+1.1 to +1.5°C</td>
<td>-5 to +5%</td>
</tr>
<tr>
<td>2070</td>
<td>+3.5 to +5.5°C</td>
<td>-16 to +16%</td>
</tr>
</tbody>
</table>

Extreme events

↑ frequency of extremely hot days and heatwaves
↑ size and frequency of extreme rainfall events
↑ frequency and length of drought conditions
↑ wind speed in most coastal areas
↑ proportion intense cyclones, possible ↓ total cyclones
**Table 2.** Mean number of hot days (maximum temperature >35°C), hot nights (minimum temperature >20°C), cold days (minimum temperature <15°C) and cold nights (minimum temperature <5°C) per annum at Katherine and Kununurra for the 1961-1990 baseline climate, the 1998-2007 period and the 2030 and 2070 future climate scenarios.

<table>
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<tbody>
<tr>
<td><strong>Katherine</strong></td>
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<td></td>
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<tr>
<td>Hot days</td>
<td>146</td>
<td>135</td>
<td>210</td>
<td>308</td>
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<tr>
<td>Hot nights</td>
<td>227</td>
<td>222</td>
<td>250</td>
<td>296</td>
</tr>
<tr>
<td>Cold days</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Cold nights</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td><strong>Kununurra</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hot days</td>
<td>197</td>
<td>174</td>
<td>247</td>
<td>320</td>
</tr>
<tr>
<td>Hot nights</td>
<td>239</td>
<td>237</td>
<td>266</td>
<td>316</td>
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<tr>
<td>Cold days</td>
<td>0</td>
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<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Cold nights</td>
<td>0</td>
<td>0</td>
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</table>

**Vulnerability of existing agricultural industries to climate change**

The climate change projections for this region do not suggest a broad scale reduction in the resources available. Rainfall has increased in recent years but there is no clear signal for changes to rainfall patterns in the future climate. The increase in extreme rainfall events and possible increase in the proportion of intense tropical cyclone suggest that storm damage is one threat that will need to be assessed for new enterprises. This will be particularly important for industries that require a lot of infrastructure and have a long lifespan, e.g. tree-based industries.

Horticultural industries have moved to the region to take advantage of the warmer climate, which presents an opportunity to extend the turn-off season of produce, and to access a reliable supply of irrigation water (compared with regions such as the Murray–Darling basin). There appear to be opportunities for warm and hot season crops to continue to expand in this region. These opportunities, together with examples of new rural industries, are explored in the 'Northern Australia' section of the 'New Industry Opportunities' chapter in this report.

**North-eastern Australia**

**Climate scenarios**

The north-eastern Australia region has a climate gradient from tropical in the north to subtropical in the south. Average annual rainfall for the 1961-1990 period was 1686 and 642 mm at Mackay and Emerald respectively, with 17% and 20% less rainfall in the 1998-2007 period (Figure 11). Rainfall change projections for the future indicate no increase in annual rainfall, and up to a 40% reduction by 2070 (Table 3).

There are significant temperature differences at the two sites due to the Mackay site being coastal and Emerald being inland. At both sites there is projected to be an increase in the frequency of hot days and hot nights, with a reduction in the number of cold nights at Emerald (Table 4).

Together with the changes in average climate outlined, changes in the intensity and frequency of extreme events are predicted with more heatwaves and extreme rainfall events, and an increase in the proportion of intense cyclones (Table 3).

**Table 3. Summary of the range of changes in mean temperature and rainfall for the north-eastern Australia region based on projections for the high emission scenario (A1FI) from the CSIRO Mark 3, GFDL and ECHAM climate models, and projected trends in the frequency and severity of extreme events.**

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Temperature change</th>
<th>Rainfall change</th>
</tr>
</thead>
<tbody>
<tr>
<td>2030</td>
<td>+1.0 to 1.5°C</td>
<td>0 to -11%</td>
</tr>
<tr>
<td>2070</td>
<td>+3.8 to 5.4°C</td>
<td>0 to -40%</td>
</tr>
</tbody>
</table>

**Extreme events**

↑ frequency of extremely hot days and heatwaves  
↓ frequency of frost  
↑ frequency of extreme rainfall events  
↑ in size of extreme rainfall events  
↑ frequency and length of drought conditions  
↑ wind speed in most coastal areas  
↑ proportion intense cyclones, possible ↓ total cyclones
North Eastern Australia

Climate scenarios

The north eastern Australia region has a climate gradient from tropical in the north to subtropical in the south. Average annual rainfall for the 1961-1990 period was 1686 and 642 mm at Mackay and Emerald respectively, with 17% and 20% less rainfall in the 1998-2007 period (Figure 11). Rainfall change projections for the future indicate no increase in annual rainfall, and up to a 40% reduction by 2070 (Table 3).

There are significant temperature differences at the two sites due to the Mackay site being coastal and Emerald being inland. At both sites there is projected to be an increase in the frequency of hot days and hot nights, with a reduction in the number of cold nights at Emerald (Table 4). Together with the changes in average climate outlined, changes in the intensity and frequency of extreme events are predicted with more heatwaves and extreme rainfall events, and an increase in the proportion of intense cyclones (Table 3).

Table 4. Mean number of hot days (maximum temperature >35°C), hot nights (minimum temperature >20°C), cold days (minimum temperature <15°C) and cold nights (minimum temperature <5°C) per annum at Mackay and Emerald for the 1961-1990 baseline climate, the 1998-2007 period and the 2030 and 2070 future climate scenarios.

<table>
<thead>
<tr>
<th>Climate</th>
<th>Rainfall</th>
<th>T min.</th>
<th>T max.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1961-1990</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1998-2007</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2030</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2070</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 11. Mean seasonal rainfall (mm), minimum (T min.) and maximum (T max.) temperature (°C) for the 1961-1990 baseline, 1998-2007 period, and 2030 and 2070 future climate scenarios at (a) Mackay and (b) Emerald.

Vulnerability of existing agricultural industries to climate change

The rainfall projections for the region suggest reduced water availability and this will be an issue in the region. The increase in extreme rainfall events and possible increase in the proportion of intense tropical cyclones suggest that storm damage is another threat that will need to be assessed for new enterprises. This will be particularly important for industries that require a lot of infrastructure and have a long lifespan, e.g. tree-based industries.

Murray–Darling basin

Climate scenarios

The Murray–Darling basin spans a broad climatic range from subtropical in the north to Mediterranean in the south of the basin, as indicated by the seasonal climate patterns for Goondiwindi and Kyabram in Figure 12. The 1998-2007 climate data show reduced rainfall at both of these sites, particularly in autumn. Average annual rainfall for the 1961-1990 period was 638 and 457 mm at Goondiwindi and Kyabram, with 7% and 15% less rainfall in the 1998-2007 period recorded at the respective sites (Figure 12). This finding is in line with reports of annual rainfall declines of 20 mm per decade since 1950 in south-eastern Australia, with
most of the reduction occurring in autumn (Gallant et al. 2007).

Climate change projections for the Murray–Darling basin for 2030 and 2070 suggest that increasing temperatures will occur (Table 5), with more hot days and nights and fewer cold days and nights (Table 6). Rainfall declines are expected to be largest in winter and spring (Figure 12). Increases in the number of heatwaves, frequency of drought conditions and fire risk are also expected (Table 5).

![Graph showing seasonal rainfall and temperature changes](image)

**Figure 12.** Mean seasonal rainfall (mm), minimum (T min.) and maximum (T max.) temperature (°C) for the 1961-1990 baseline, 1998-2007 period, and 2030 and 2070 future climate scenarios at (a) Goondiwindi and (b) Kyabram.

<table>
<thead>
<tr>
<th>Climate</th>
<th>Rainfall</th>
<th>T min.</th>
<th>T max.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1961-1990</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>1998-2007</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2030</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2070</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Legend**
- ▲: Frequency of extremely hot days and heatwaves
- ▼: Frequency of extremely cold days and cold nights
- ▲: Frequency of frost, possible increase in severity
- ▼: Frequency of extreme rainfall events
- ▲: Frequency and length of drought conditions
- ■: Substantial increase in fire weather risk

Table 5. Summary of the range of changes in mean temperature and rainfall for the Murray–Darling basin region based on projections for the high emission scenario (A1FI) from the CSIRO Mark 3, GFDL and ECHAM climate models, and projected trends in the frequency and severity of extreme events.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Temperature change</th>
<th>Rainfall change</th>
</tr>
</thead>
<tbody>
<tr>
<td>2030</td>
<td>+1.0 to +1.5°C</td>
<td>0 to -11%</td>
</tr>
<tr>
<td>2070</td>
<td>+3.7 to +5.4°C</td>
<td>-3 to -39%</td>
</tr>
</tbody>
</table>

**Extreme events**
- ▲: Frequency of extremely hot days and heatwaves
- ▼: Frequency of extremely cold days and cold nights
- ▲: Frequency of frost, possible increase in severity
- ▲: Frequency of extreme rainfall events
- ▼: Frequency and length of drought conditions
- ■: Substantial increase in fire weather risk

Table 6. Mean number of hot days (maximum temperature >35°C), hot nights (minimum temperature >20°C), cold days (minimum temperature <15°C) and cold nights (minimum temperature <5°C) per annum at Goondiwindi and Kyabram for the 1961-1990 baseline climate, the 1998-2007 period and the 2030 and 2070 future climate scenarios.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Goondiwindi</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hot days</td>
<td>32</td>
<td>40</td>
<td>55</td>
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<tr>
<td>Hot nights</td>
<td>45</td>
<td>52</td>
<td>78</td>
<td>155</td>
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<td>Cold days</td>
<td>9</td>
<td>5</td>
<td>4</td>
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<tr>
<td>Cold nights</td>
<td>47</td>
<td>49</td>
<td>33</td>
<td>6</td>
</tr>
<tr>
<td><strong>Kyabram</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hot days</td>
<td>13</td>
<td>19</td>
<td>19</td>
<td>41</td>
</tr>
<tr>
<td>Hot nights</td>
<td>5</td>
<td>9</td>
<td>10</td>
<td>33</td>
</tr>
<tr>
<td>Cold days</td>
<td>87</td>
<td>64</td>
<td>66</td>
<td>19</td>
</tr>
<tr>
<td>Cold nights</td>
<td>100</td>
<td>99</td>
<td>80</td>
<td>35</td>
</tr>
</tbody>
</table>
Vulnerability of existing agricultural industries to climate change

Irrigation water availability, quality and price will be the key drivers of changes in the existing irrigated agricultural industries in the Murray–Darling basin. River flow, and therefore irrigation water availability, is particularly sensitive to reduced rainfall and increased temperature, with estimates of a 10% reduction in rainfall leading to a 35% reduction in river flows (Jones et al. 2006). In addition, increased competition for water for urban and environmental uses is certain.

The CSIRO Sustainable Yields project reported that declines in surface water availability are more likely, and likely to be more substantial, in the southern Murray–Darling basin compared to the northern catchments of the region. By 2030, median climate change projections suggest a 9% reduction in surface water availability in the north of the basin compared to a 13% reduction in the south. Water flows are predicted to be most heavily impacted in the driest years, with reductions of 35-50% in northern Victorian catchments and more severe consequences with further climate change (CSIRO 2008). The existing drought from 1997 has seen the lowest inflows in the southern Murray–Darling basin on record, a 1 in 300 year event (CSIRO 2008). This drought period is in part attributable to climate change, with CSIRO and BoM (2007) indicating that such conditions are likely to become more common. This suggests that less irrigation water will be available for agriculture in this region, and its availability will be more variable.

In conjunction with reduced irrigation water availability, increasing water salinity levels are also likely to impact on agricultural production systems. The mean salinity of water at Adelaide (sourced from the lower reaches of the River Murray) was simulated to increase from 468 to 672 (EC units) by 2030 associated with a 3-11% decline in river flow, and increased further to 5216 EC by 2070 associated with 60-100% declines in river flows across the catchments in the Murray–Darling basin (Quiggan et al. 2008).

In area, pasture and hay production is the dominant irrigated land use in the Murray–Darling basin (820K ha), followed by cereal and cotton (467K and 426K ha respectively), and horticulture and viticulture (200K ha combined) (CSIRO 2008). Recent analyses of water trading have shown that as the price of water increases above $300/ML, it is traded away from broadacre pasture and crop production to more intensive uses such as horticulture and viticulture. As water availability becomes more restricted this trend can be expected to continue. The potential for new irrigated and dryland industries in the Murray–Darling basin is discussed in the 'New Industry Opportunities' section.
Marginal cropping fringe of southern Australia

Climate scenarios

The marginal cropping fringe of southern Australia has a Mediterranean climate with cool wet winters and hot, dry summers. The region has relatively low annual rainfall, with mean annual rainfall (1961-1990) being 313 mm at Merredin and 382 mm at Birchip (Figure 13). Recent climate records show below average rainfall in winter and spring at both sites, while autumn rainfall at Birchip has been particularly low. Climate change projections for the region indicate that rainfall will continue to decline, by up to 55% in 2070 (Table 7).

Warming is predicted to increase the number of hot days and nights, and reduce the number of cold days and nights across the region (Table 8). While a comparison of the number of hot days, hot nights, and cold days in the 1961-1990 and 1998-2007 data indicates a warming trend, there was also an increase in the number of cold nights during this period. This suggests a possible issue with frost, and is correlated with projections for minimum temperatures to rise more slowly than the average temperature across southern Australia (CSIRO and BoM 2007).

Changes in the frequency of extreme events are expected, with more hot days and heat waves, increased length of drought conditions, and greater fire weather risk (Table 7).

Figure 13. Mean seasonal rainfall (mm), minimum (T min.) and maximum (T max.) temperature (°C) for the 1961-1990 baseline, 1998-2007 period, and 2030 and 2070 future climate scenarios at (a) Merredin and (b) Birchip.

Table 7. Summary of the range of changes in mean temperature and rainfall for the marginal cropping zone of southern Australia region based on projections for the high emission scenario (A1FI) from the CSIRO Mark 3, GFDL and ECHAM climate models, and projected trends in the frequency and severity of extreme events.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Temperature change</th>
<th>Rainfall change</th>
</tr>
</thead>
<tbody>
<tr>
<td>2030</td>
<td>+1.0 to +1.2°C</td>
<td>-4 to -15%</td>
</tr>
<tr>
<td>2070</td>
<td>+3.6 to +4.3°C</td>
<td>-15 to -55%</td>
</tr>
</tbody>
</table>

Extreme events

↑ frequency of extremely hot days and heatwaves

Moderate ↓ frequency of frost, possible increase in severity

↑ frequency of extreme rainfall events

↑ in size of extreme rainfall events (except in winter/spring)

↑ frequency and length of drought conditions.

Substantial ↑ in fire weather risk
Table 8. Mean number of hot days (maximum temperature >35°C), hot nights (minimum temperature >20°C), cold days (minimum temperature <15°C) and cold nights (minimum temperature <5°C) per annum at Merredin and Birchip for the 1961-1990 baseline climate, the 1998-2007 period and the 2030 and 2070 future climate scenarios.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Merredin</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hot days</td>
<td>38</td>
<td>43</td>
<td>53</td>
<td>80</td>
</tr>
<tr>
<td>Hot nights</td>
<td>22</td>
<td>21</td>
<td>38</td>
<td>70</td>
</tr>
<tr>
<td>Cold days</td>
<td>25</td>
<td>15</td>
<td>13</td>
<td>2</td>
</tr>
<tr>
<td>Cold nights</td>
<td>51</td>
<td>61</td>
<td>34</td>
<td>12</td>
</tr>
<tr>
<td><strong>Birchip</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hot days</td>
<td>21</td>
<td>26</td>
<td>27</td>
<td>50</td>
</tr>
<tr>
<td>Hot nights</td>
<td>9</td>
<td>10</td>
<td>14</td>
<td>33</td>
</tr>
<tr>
<td>Cold days</td>
<td>65</td>
<td>49</td>
<td>48</td>
<td>10</td>
</tr>
<tr>
<td>Cold nights</td>
<td>82</td>
<td>89</td>
<td>62</td>
<td>20</td>
</tr>
</tbody>
</table>

Vulnerability of existing agricultural industries to climate change

Declining rainfall in this low rainfall environment will place existing agricultural industries at risk in the longer term. While there is capability to adapt annual cropping systems (e.g. through using different varieties, sowing times, fallowing and removing high risk crops from the rotation (Laing et al. 2009)), droughts and climate variability will increase pressure on these industries. A return to grazing-based industries is expected and new rural industries suited to drier environments are required. These issues are discussed in the ‘New Rural Industry Opportunities’ chapter.

Southern Australia high rainfall

Climate scenarios

The southern Australia high rainfall zone has a temperate climate. Mean annual rainfall (1961-1990) at Hamilton was 693 mm and at Ellinbank was 1090 mm, but declined by 9% at Hamilton and 18% at Ellinbank in the 1998-2007 climate record (Figure 14). Most of the decline in rainfall occurred in autumn and winter. Further declines in rainfall are predicted with climate change (Table 9). In these cool climates, the main effect of temperature is a reduction in the number of cold days (Table 10). Cold nights are also expected to decline, but frost will remain an important consideration because minimum temperatures are expected to rise more slowly than average temperature across southern Australia (CSIRO and BoM 2007). Changes in the frequency of extreme events are expected to be similar to those in the Murray–Darling basin (Table 9).

Figure 14. Mean seasonal rainfall (mm), minimum (T min.) and maximum (T max.) temperature (°C) for the 1961-1990 baseline, 1998-2007 period, and 2030 and 2070 future climate scenarios at (a) Hamilton and (b) Ellinbank.
Table 9. Summary of the range of changes in mean temperature and rainfall for the southern Australia high rainfall region based on projections for the high emission scenario (A1FI) from the CSIRO Mark 3, GFDL and ECHAM climate models, and projected trends in the frequency and severity of extreme events.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Temperature change</th>
<th>Rainfall change</th>
</tr>
</thead>
<tbody>
<tr>
<td>2030</td>
<td>+0.8 to +1.0°C</td>
<td>-4 to -8%</td>
</tr>
<tr>
<td>2070</td>
<td>+2.8 to +3.7°C</td>
<td>-16 to -30%</td>
</tr>
</tbody>
</table>

**Extreme events**

- ↑ frequency of extremely hot days and heatwaves
- Moderate ↓ frequency of frost
- ↑ frequency of extreme rainfall events
- ↑ in size of extreme rainfall events (except in winter/spring)
- ↑↑ frequency and length of drought conditions
- ↑ wind speed in most coastal areas
- Substantial ↑ in fire weather risk

Table 10. Mean number of hot days (maximum temperature >35°C), hot nights (minimum temperature >20°C), cold days (minimum temperature <15°C) and cold nights (minimum temperature <5°C) per annum at Hamilton and Ellinbank for the 1961-1990 baseline climate, the 1998-2007 period and the 2030 and 2070 future climate scenarios.

<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td><strong>Hamilton</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hot days</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>16</td>
</tr>
<tr>
<td>Hot nights</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Cold days</td>
<td>137</td>
<td>115</td>
<td>118</td>
<td>56</td>
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<tr>
<td>Cold nights</td>
<td>100</td>
<td>88</td>
<td>80</td>
<td>36</td>
</tr>
<tr>
<td><strong>Ellinbank</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hot days</td>
<td>4</td>
<td>4</td>
<td>6</td>
<td>14</td>
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<tr>
<td>Hot nights</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>Cold days</td>
<td>119</td>
<td>102</td>
<td>102</td>
<td>36</td>
</tr>
<tr>
<td>Cold nights</td>
<td>57</td>
<td>56</td>
<td>46</td>
<td>13</td>
</tr>
</tbody>
</table>

Vulnerability of existing agricultural industries to climate change

Livestock-based industries are currently the dominant land use in these areas. Due to the high rainfall in the region, there is capacity for those industries to continue but increased competition for land from cereal cropping industries is expected (Harle et al. 2007). Indeed, land use changes in south-western Victoria and south-eastern South Australia show an expansion of dryland cropping by 143,000 ha, dairying by 90,000 ha, viticulture by 7,000 ha and blue gum plantations by 2,000 ha at the expense of broadacre grazing in the period 1991 to 2006 (Schirmer et al. 2008). Compared to regions like the southern marginal cropping zone and Murray–Darling basin, dryland agriculture in this region has a number of mainstream options available in future drier climate scenarios.

South-west Australia high rainfall

Climate scenarios

The south-west Australia high rainfall zone has a Mediterranean climate with annual average rainfall (1961-1990) of 820 mm at Bunbury and 788 mm at Albany (Figure 15). In the 1998-2007 period, annual rainfall declined by 10% at Bunbury and 7% at Albany, with most of the decline occurring in winter (Figure 15). In future climate scenarios, rainfall is predicted to decline by up to 55% (Table 11), with the decreases concentrated in winter and spring (Figure 15). In these cool climates, the main effect of increasing temperature is observed in the predicted data for 2070 (Table 12). There has been an increase in number of cold nights at Bunbury between the 1961-1990 baseline climate and the 1998-2007 period (Table 12) but the frequency of cold nights is expected to decline in the future. Changes in the frequency of extreme events (Table 11) are expected to be similar to those in the Murray–Darling basin (Table 5), including increased frequency of drought conditions, heat waves and days with high fire weather risk.

Vulnerability of existing agricultural industries to climate change

Livestock-based industries are currently the dominant land use in the south-western high rainfall zone. Due to the high rainfall in the region, there is capacity for those industries to continue but increased competition for land from cereal cropping industries is expected (Harle et al. 2007). Compared to regions like the southern marginal cropping zone and Murray–Darling basin, dryland agriculture in this region has a number of mainstream options because it is in a higher rainfall zone.
The south west Australia high rainfall zone has a Mediterranean climate with annual average rainfall (1961-1990) of 820 mm at Bunbury and 788 mm at Albany (Figure 15). In the 1998-2007 period, annual rainfall declined by 10% at Bunbury and 7% at Albany, with most of the decline occurring in winter (Figure 15). In future climate scenarios, rainfall is predicted to decline by up to 55% (Table 11), with the decreases concentrated in winter and spring (Figure 15).

In these cool climates, the main effect of increasing temperature is observed in the predicted data for 2070 (Table 12). There has been an increase in number of cold nights at Bunbury between the 1961-1990 baseline climate and the 1998-2007 period (Table 12) but the frequency of cold nights is expected to decline in the future. Changes in the frequency of extreme events (Table 11) are expected to be similar to those in the Murray-Darling basin (Table 5), including increased frequency of drought conditions, heat waves and days with high fire weather risk.

Figure 15. Mean seasonal rainfall (mm), minimum (T min.) and maximum (T max.) temperature (°C) for the 1961-1990 baseline, 1998-2007 period, and 2030 and 2070 future climate scenarios at (a) Bunbury and (b) Albany.

### Table 11. Summary of the range of changes in mean temperature and rainfall for the south-western Australia high rainfall region based on projections for the high emission scenario (A1FI) from the CSIRO Mark 3, GFDL and ECHAM climate models, and projected trends in the frequency and severity of extreme events.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Temperature change</th>
<th>Rainfall change</th>
</tr>
</thead>
<tbody>
<tr>
<td>2030</td>
<td>+0.7 to +0.9°C</td>
<td>-5 to -16%</td>
</tr>
<tr>
<td>2070</td>
<td>+2.7 to +3.4°C</td>
<td>-20 to -55%</td>
</tr>
</tbody>
</table>

**Extreme events**

- ↑ frequency of extremely hot days and heatwaves.
- Moderate ↓ frequency of frost
- ↑ frequency of extreme rainfall events
- ↑ in size of extreme rainfall events (except in winter/spring)
- ↑↑ frequency and length of drought conditions.
- ↑ wind speed in most coastal areas
- Substantial ↑ in fire weather risk

### Table 12. Mean number of hot days (maximum temperature >35°C), hot nights (minimum temperature >20°C), cold days (minimum temperature <15°C) and cold nights (minimum temperature <5°C) per annum at Bunbury and Albany for the 1961-1990 baseline climate, the 1998-2007 period and the 2030 and 2070 future climate scenarios.

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td><strong>Bunbury</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Hot days</td>
<td>3</td>
<td>5</td>
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<td>16</td>
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<td>Hot nights</td>
<td>5</td>
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<td>11</td>
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<td>0</td>
</tr>
<tr>
<td>Cold nights</td>
<td>7</td>
<td>24</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td><strong>Albany</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hot days</td>
<td>4</td>
<td>3</td>
<td>5</td>
<td>11</td>
</tr>
<tr>
<td>Hot nights</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>19</td>
</tr>
<tr>
<td>Cold days</td>
<td>33</td>
<td>29</td>
<td>23</td>
<td>2</td>
</tr>
<tr>
<td>Cold nights</td>
<td>14</td>
<td>13</td>
<td>9</td>
<td>0</td>
</tr>
</tbody>
</table>
Conclusion

Broadacre irrigated agriculture in the Murray–Darling basin is very highly vulnerable to the impacts of climate change. It is expected that high value irrigated crops will continue to be grown in the Murray–Darling basin, but there may be some changes to the mix of crops to deal with lower and more variable irrigation allocations, and the area of irrigated pasture and crops will contract with a return to dryland agricultural activities. In this region three agricultural production opportunities have been identified for future industries:

- High value irrigated crops – that rely on adequate supplies of high quality irrigation water to ensure production and product quality.
- Resilient irrigated crops – that have lower water requirements and/or can tolerate periods when irrigation cannot be supplied (due to low water availability or high price), then rapidly respond when irrigation water becomes available.
- Dryland farming systems – with declining total amounts of irrigation water there will be a conversion to dryland agriculture. Warmer temperatures and reduced rainfall will cause the environment to become drier. This also applies to the southern marginal cropping fringe region.

The higher rainfall zones of southern Australia, while similarly impacted by increasing temperatures and percent rainfall reduction, have more mainstream agricultural options available to them. For example, in south-west Victoria the area of cereal cropping has increased in recent years as conditions have become more favourable for annual cropping systems (e.g. less water logging), and this can be expected to continue.

Climate change projections for northern Australia do not indicate the same rainfall decline expected across southern Australia. Improved access to water in this region may lead to an expansion of tropical and heat tolerant agricultural industries. These opportunities are further discussed in the 'New Industry Opportunities' chapter.
New rural industry opportunities

Irrigated agriculture in the southern Murray–Darling basin

Selection criteria

Three production opportunities were identified for enterprises in the Murray-Darling basin under future climate scenarios: (1) high value irrigated crops; (2) resilient irrigated crops; and (3) dryland farming systems. The plant characteristics required to take advantage of each of these production opportunities are different. The options for irrigated crops will be considered firstly, followed by the options for dryland systems (including the southern marginal cropping fringe).

High value irrigated crops rely on adequate supplies of high quality irrigation water to ensure production and product quality. The recent trends in water trading have seen water traded away from broadacre irrigated agriculture, such as dairy and rice, to higher value horticulture production such as pomefruit production and viticulture as the water price rises. With increasingly limited irrigation water supplies brought about by lower rainfall and increased water demand for urban and environmental uses, this trend is expected to continue so the financial return per ML irrigation water applied is a critical selection criterion for new rural industries. Production systems that require a consistently large amount of good quality irrigation water will need to produce a high value product to ensure their financial sustainability in an era of higher water prices. Crops in this ecological niche include traditional horticultural industries such as pomefruit and citrus. Important plant characteristics for high value irrigated crops in future climates will be:

- Water use efficiency – plants with higher water use efficiency will make better use of the available water resources.
- Heat tolerance – to cope with the increased frequency of hot days and heatwaves.
- Frost tolerance – even with warming, frost is likely to remain an issue in the southern Murray-Darling basin, in part associated with longer dry periods.
- Lower chilling requirements (vernalisation) – warming may reduce the number of cold days, restricting production of crops that have a vernalisation requirement.

High value irrigated crops will continue to be important in future climates. Resilient irrigated crops present a new opportunity to utilise lower and more variable irrigation water supplies more efficiently.

Resilient irrigated crops require the same traits as those outlined above and additional attributes that allow them to tolerate low water supplies. Resilient irrigated crops have lower water requirements, can tolerate periods when irrigation cannot be supplied (due to low water availability or high price), and/or can utilise lower quality water, then rapidly respond when irrigation water becomes available. Resilience to low water availability can be achieved with drought tolerant perennial species or annual plant based systems, where the crop is planted only when water will be available. This resilience needs to be combined with temperature tolerances and the growing of the crop needs to be economically viable.

Incorporating more resilient irrigated crops into future agricultural systems will help to achieve adaptation to lower and more variable irrigation supplies and increase the range of crops grown, thereby reducing the risk of damage from extreme events.

It is clear that there will not be one crop or system that meets all of these criteria because some of these plant attributes are complementary (e.g. heat tolerance and low vernalisation requirement) while others may not be (e.g. plants that use the C₄ photosynthetic pathway are more heat tolerant but also more susceptible to frost). Improvements to agricultural systems management, e.g. by improving irrigation supply systems and utilising seasonal climate forecasting, will also
be important components in adaptation to projected future climates.

**Resilient irrigated crops**

**Resilience to low irrigation water availability**

Resilience to low irrigation water availability can be achieved by using perennial plants with a combination of low total water use, high water use efficiency, and the ability to survive during periods of low water allocation but rapidly resume production when water is available; or annual plants that can be sown opportunistically based on water availability. The resilience of these systems provides the flexibility to respond to irrigation water availability and price on a seasonal basis without compromising future production.

The traditional Australian irrigated horticultural industries, such as citrus and pomefruit, have developed in an era of full water allocations and generally lack resilience to low water availability. This is because relatively small reductions in irrigation supply result in reduced fruit size, with heavy price penalties, and trees take 2-3 years to achieve full production after a dry year (Falivene et al. 2006). Emerging crops with greater resilience to low water availability, such as the olive, use similar quantities of water as citrus and pomefruit for full production, but substantially less to maintain lower levels of production (Figure 16; ICMS 2007a, b, c, d & e). To maintain low levels (10%) of their yield potential, olives use about 27% of their water requirement for full production compared to 36, 42 and 56% for grapes, pomefruit and citrus, respectively (Figure 17). While there are no hard data available to substantiate the claim, anecdotal evidence also suggests that olives will also resume full production more rapidly after a period of moisture stress than citrus.

![Figure 16. Annual water requirement (ML/ha) for 100, 90, 50 and 10% yield potential of pomefruit, citrus, olive and grape crops in the Upper Murray irrigation zone of South Australia.](image)

![Figure 17. Percentage of 100% yield potential water requirement for 90, 50 and 10% yield potential of pomefruit, citrus, olive and grape and in the Upper Murray irrigation zone of South Australia.](image)
New rural industry options that have greater resilience to low water availability are identified and described below.

**Olives**

The olive (*Olea europaea*) is a hardy tree native to the Mediterranean region (Sweeney & Davies 2004). Although the olive tree can be grown across a range of climates it does require cool winter temperatures for vernalisation (though olive varieties may vary in this respect) and warm, dry summers to ripen the fruit. It is sensitive to temperature below -5°C and while tolerant to light frost, frosts that occur early or late in the year can cause damage to the maturing fruit and flowers respectively (Taylor & Burt 2007). While much of the world's olive production is under rain-fed conditions, most olive orchards in Australia are irrigated to achieve good yields (Sweeney & Davis 2004). The drought tolerance and lower water requirement compared to citrus and pomefruit make the plant a more resilient irrigated crop (Figure 16). Well-drained soils are preferred.

Olives can be produced for either the oil or table markets using different varieties. Fruit for oil should be processed as soon as possible after harvesting to reduce oxidation which produces off-flavours in the oil (Sweeney & Davies 2004).

Along with irrigated systems, the potential for rain-fed olive production in the medium rainfall zones of southern Australia is worthy of further exploration particularly if the trees can be considered as a carbon sequestration option, providing a second income stream from the plantation.

**Jojoba**

Jojoba (*Simmondsia chinensis*) is an extremely drought tolerant perennial shrub that produces a liquid wax that is used in cosmetics and industrial applications (Milthorpe 2004). The plant is common in Sonoran desert regions of northern Mexico, California and Arizona (Benzioni 1997). Much of the inland cereal growing belt of eastern Australia has a climate suitable for jojoba, although a minimum annual rainfall of 450 mm or supplemental irrigation is required. Soils must be well-drained. Yields of established rainfed crops are about 1 t seed/ha and up to 2 t/ha when irrigated (Milthorpe 2004). The crop is relatively easy to integrate with other land uses because the timing of management operations is not as critical as for other industries such as fresh fruit, making it a good diversification option (Milthorpe 2004).

The jojoba plant produces a seed the size of a peanut which is crushed using oilseed presses to yield the liquid wax (Milthorpe 2004).

**Pomegranates**

The pomegranate (*Punica granatum*) is a drought tolerant perennial fruit-bearing tree that is native to the Middle East (Johnson 2002). It can be grown across a wide range of climatic zones from temperate to subtropical, but is best suited to Mediterranean climates as it requires winter chilling (vernalisation) to break dormancy and hot dry summers for fruit ripening (DAFWA 2008). While the tree is drought tolerant, it does require an irrigation water supply for production estimated to be 5-8ML/ha from September to April in south-west Western Australia (DAFWA 2008). The plant is also frost tolerant. Pomegranate trees are moderately tolerant of salinity and prefer well-drained soils but can withstand short periods of waterlogging (DAFWA 2009).

Pomegranates can be grown for either the fresh or juice markets. As a fresh fruit the pomegranate can be stored for up to 7 months at 0-5°C and 80-85% humidity without spoilage, while the juice can be extracted with modified grape crushing equipment making proximity to grape processing plants advantageous (DAFWA 2009).
Capers

The caper plant (*Capparis spinosa*) is a perennial plant that is native to the Mediterranean region, and is tolerant of drought, salinity and high temperatures. It can be grown in regions with a Mediterranean climate and 250-680 mm annual rainfall, with supplemental irrigation applied where available (Trewartha & Trewartha 2004). The plant is sensitive to frost in its growing season. Well drained soils are essential. In the establishment phase the plant is very susceptible to drought stress but once established it is very hardy. Capers have a range of culinary uses, including edible buds, berries and leaves. The plant is harvested by hand, making the process very labour intensive. Reducing the cost of harvesting is a key issue for the industry (Trewartha & Trewartha 2005).

Quandong

The quandong (*Santalum acuminatum*) is an Australian native tree or shrub that produces a fruit used for a range of culinary processes (Lethbridge 2004). The plant is highly drought and salinity tolerant but cultivation is currently limited by a lack of understanding of its semi-parasitic nature (the plant attaches itself to the roots of one or more other plants through haustoria and obtains nitrogen and some water in this manner). The plant requires a climate with high light intensity and low humidity. Well-drained soils are essential as the plant does not tolerate water-logging. Irrigation requirements are dependent on the needs of the host-plant (Lethbridge 2004). Host plants can be other trees or grasses.

Bush tomato

The bush tomato (*Solanum centrale*) is native to arid regions of central Australia and has been propagated in South Australia and western New South Wales (Robins & Ryder 2004). It is used primarily as a herb/spice product. The plant is adapted to low and variable rainfall environments and can grow and produce fruit following a single rainfall event of sufficient quantity. The plant can be grown as an annual, planted early in spring, or preferably as a perennial on well-drained soils. It is susceptible to frost damage. Irrigation is required, and the plant has reasonable salinity tolerance (Robins & Ryder 2004).

Desert lime

The desert lime (*Citrus glauca*) is a citrus tree native to semi-arid regions of eastern Australia. It is extremely tolerant of a wide range of climatic conditions including drought, heat and frost (Macintosh 2004). It is usually found on clay or heavy clay soil types. The species will respond to fertiliser and irrigation.

Cacti

Cacti that produce an edible fruit, including yellow pitaya (*Selenicereus megalanthus*), red pitaya (*Hylocereus spp.*) and koubo pitaya (*Cereus peruvianus*) have considerably lower water requirements and higher water-use efficiency than traditional horticultural crops (Table 13; Mizrahi et al. 2007). These plants use the Crassulacean acid metabolism (CAM) photosynthetic pathway where plants fix carbon during the night, allowing them to keep their stomata closed during the day, reducing water loss and therefore increasing water use efficiency. The CAM photosynthetic pathway is common to plants adapted to arid environments but also includes the pineapple. In arid regions Mizrahi et al. (2007) recommends greater research into the potential of CAM species.
Table 13. Comparative yield, irrigation requirement and water use efficiency of CAM and C₃ photosynthetic pathway crops grown in the Negev Desert of Israel.

<table>
<thead>
<tr>
<th>Fruit crop</th>
<th>Yield (t/ha)</th>
<th>Irrigation required (ML/ha)</th>
<th>Water use efficiency (t fruit/ML water)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>C₃ plants</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pear</td>
<td>15</td>
<td>6.9</td>
<td>2.2</td>
</tr>
<tr>
<td>Peach</td>
<td>12</td>
<td>6.3</td>
<td>1.9</td>
</tr>
<tr>
<td>Avocado</td>
<td>12 - 20</td>
<td>9.4</td>
<td>1.3 - 2.1</td>
</tr>
<tr>
<td>Various citrus</td>
<td>35 - 80</td>
<td>10.0 - 12.0</td>
<td>3.5 - 6.6</td>
</tr>
<tr>
<td><strong>CAM plants</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Koubo (Cereus peruvianus)</td>
<td>25</td>
<td>1.2 - 1.6</td>
<td>15.6 - 20.8</td>
</tr>
<tr>
<td>Cactus pear (Opuntia ficus-indica)</td>
<td>30</td>
<td>2.5</td>
<td>12.0</td>
</tr>
<tr>
<td>Cacti (Hylocereus polyrhizus, H. undatus, Selenicereus megalanthus)</td>
<td>35</td>
<td>1.2 - 1.6</td>
<td>21.9 - 29.2</td>
</tr>
</tbody>
</table>

Source: Mizrahi et al. (2007).

Annual plant based systems

Irrigated annual cropping systems also have resilience to low water availability as sowing decisions can be based on water availability in the catchments. An additional advantage of annual plant based systems is that the potential speed of adaptation of new cultivars or species better suited to a changing climate is faster and easier compared to long-lived perennial crops (Cavagnaro et al. 2006). One example of a high-value, summer-growing irrigated annual crop is azuki bean (Vigna angularis) (Hamilton 2004). This crop requires very careful irrigation management because it is not tolerant of water stress or water logging. There is potential to use azuki bean as a short season summer crop in a double-cropping system with wheat (Hamilton 2004).

Resilience to salinity

Dates

Dates (Phoenix dactylifera) have a much higher salinity tolerance than olives, pomefruit and grapes (Figure 18; Skewes et al. 2007). The date plant is drought resistant but has a high water requirement for full production (15 ML/ha, compared with data in Figure 16), with mature crops in central Australia estimated to require 27 ML/ha (Kenna 1996). Consequently, the date palm is suited to areas where there is a large quantity of lower quality water available, and could potentially use recycled water. The date plant is tolerant of high and low temperature extremes, and requires long, hot, dry summers for ripening and harvest (Burt 2005). More than 2000 heat units (°C, sum of maximum daily temperature minus 18°C) per annum are required to reach date maturity. The date plant can grow on a wide range of soil types, but free-draining soils are preferable.
Australia estimated to require 27 ML/ha (Kenna 1996). Consequently, the date palm is suited to areas where there is a large quantity of lower quality water available, and could potentially use recycled water. The date plant is tolerant of high and low temperature extremes, and requires long, hot, dry summers for ripening and harvest (Burt 2005). More than 2000 heat units (°C, sum of maximum daily temperature minus 18°C) per annum are required to reach date maturity. The date plant can grow on a wide range of soil types, but free-draining soils are preferable.

**Figure 18.** Soil salinity threshold (dS/m) for 0, 10, 25 and 50% yield loss in pomefruit, citrus, olives, grapes and date palm. Note that the pomefruit and citrus lines overlay one another.

The relative strengths and weaknesses of each of the resilient irrigated new enterprise options in terms of water requirement, resilience to low water availability, and salinity tolerance, is compared to grape, citrus and horticultural options in Table 14. No plants are perfectly adapted, but all offer some comparative advantage. Individual growers will make decisions based on their physical and financial resources and personal interest.

**Table 14. Comparative rating of new and traditional irrigated crop water requirement, resilience to low water availability and salinity tolerance**

<table>
<thead>
<tr>
<th>Crop</th>
<th>Water requirement for full production</th>
<th>Resilience to drought/low irrigation water</th>
<th>Salinity tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>New rural industries</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Olives</td>
<td>High</td>
<td>High</td>
<td>Moderate</td>
</tr>
<tr>
<td>Jojoba</td>
<td>High</td>
<td>High</td>
<td>Moderate</td>
</tr>
<tr>
<td>Pomegranates</td>
<td>High</td>
<td>High</td>
<td>Moderate</td>
</tr>
<tr>
<td>Capers</td>
<td>Low</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Quandong, bush tomato, desert lime</td>
<td>Low-Moderate</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Cacti</td>
<td>Low</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Dates</td>
<td>Very High</td>
<td>High</td>
<td>Very High</td>
</tr>
<tr>
<td><strong>Traditional industries</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wine grapes</td>
<td>High</td>
<td>Low</td>
<td>Moderate</td>
</tr>
<tr>
<td>Citrus</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Pomefruit</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
</tr>
</tbody>
</table>

**Other species which may be worth considering as resilient irrigated crops include**

- Acerola (*Malpighia glabra*)
- Black sapote (*Diospyros digyna*)
- Chilean wine palm (*Jubaea chilensis*)
- Jujube or ber (*Zizyphus mauritiana*)
- Marula (*Sclerocarya birrea*)
- Otaheite apple (*Spondias cytherea*)
- Sandalwood (*Santalum spicatum*)
- White leadtree (*Leucaena leucocephala*)
- Almond (*Prunus amygdalus*)
- Blackberry jam fruit (*Randia formosa*)
- Feijoa or pineapple guava (*Feijoa sellowiana*)
- Kumquat (*Fortunella margarita*)
- Loquat (*Eriobotrya japonica*)
- Mayten (*Maytenus boaria*)
- Pistachio (*Pistacia vera*)
- Sapodilla (also salt tolerant) (*Manilkara achras*)
- White Mulberry (*Morus alba*)
- Argan (*Argania spinosa*)
- Carob (*Ceratonia siliqua*)
- Fig (*Ficus carica*)
- Loquat (*Eriobotrya japonica*)
- Mayten (*Maytenus boaria*)
- Pistachio (*Pistacia vera*)
- Sapodilla (also salt tolerant) (*Manilkara achras*)
- White Mulberry (*Morus alba*)
- Avocado (*Persea americana*)
- Che or Chinese mulberry (*Cudrana tricuspida*)
- Jelly palm (*Butia capitata*)
- Mandarine (*Citrus reticulata*)
- Mongongo nut (*Schinzophyton raufanenii*)
- Monkey orange (*Strychnos cocculoides*)
- Raisin tree (*Hovenia dulcis*)
- Tamarind (*Tamarindus indica*)
- White Mulberry (*Morus alba*)
- White sapote (*Casimiroa edulis*) and Yeheb nut (*Cordeauxia edulis*)
Feasibility of New rural industry options

The potential for resilient irrigated crops to replace the current mix of irrigated crops in future climates relies on the resilient crops making more efficient use of the lower and more variable irrigation water supply expected in future climates. While there is little production and economic data under Australian conditions available for most of the new crop opportunities identified in this report, a comparison of irrigated citrus (traditional crop) and olive (resilient irrigated crop) orchards is used to demonstrate the benefit of resilient irrigated crops under limited irrigation water scenarios.

To assess the benefits of resilient irrigated systems, hypothetical irrigated citrus and olive orchards were compared using two irrigation management approaches. In each case a 50 ha orchard was compared with different percentages of irrigation water allocation. The major assumptions about crop water-use, crop production and prices are outlined below:

- **Crop water-use:** based on the water use and yield potential estimates presented in Figure 16, and assuming 2.5 ML/ha of water available from rainfall.
- **Production:** reference figures for production at 100% yield potential of 30 t fruit/ha for citrus and 2500 l oil/ha for olives were used.
- **Price:** $350/t for citrus and $4.2/l for olive oil.

In the first irrigation management approach, the area of the orchard that can be irrigated at 90% yield potential with irrigation water allocations of 80, 60, 40 and 20% are shown in Figure 19. At each level of water allocation, the area of irrigated olives is greater than the area of irrigated citrus, due to the lower water use by olives at yield potential less than 100%.

Using reference figures above for production and price, the gross values of production per ML irrigation water is higher for citrus than olive when irrigated at 100% yield potential, i.e. at 100% water allocation ($1,641 v. $1,522/ML respectively). However when water is limited and irrigation is applied to achieve 90% of yield potential, the situation is reversed and the gross value of production is greater for olives compared to citrus ($1,688 and $1,817/ML for citrus and olives respectively). This analysis demonstrates the advantage of lower water use plant systems. It does not consider the more rapid recovery of production following water stress of olives compared to citrus, which would further benefit olive production when water allocations return to higher levels.

In the second irrigation management example, a different management system was used and the impacts on the production of citrus and olive orchards were compared using the irrigation water allocations for the last 10 years in the Goulburn-Broken catchment. Water allocations in the Goulburn-Broken catchment have been declining and increasingly variable over the last 10 years (Figure 20) and therefore provide a case-study of water availability relevant to future climate scenarios. Across this 10 year period water allocations averaged 80%, similar to what is projected for climate scenarios in 2030 to 2050.

**Figure 19.** Area of a 50 ha citrus or olive orchard that could be irrigated to 90% yield potential with 80, 60, 40 or 20% irrigation allocations.
In order to do this analysis several simplifying assumptions were made about water management and crop responses in the orchards:

- In years when the full (100%) water allocation was granted the orchards were irrigated to achieve 100% yield potential.

- When the irrigation allocation was less than 100%; the first management decision was to irrigate the orchard at 90% yield potential.

- If there was insufficient water to irrigate the whole orchard at this 90% yield potential the remainder of the orchard area was irrigated at 10% yield potential. It was assumed that irrigating at 10% yield potential would keep the crop in a ‘responsive’ phase so that production in future years would not be compromised.

- If there was insufficient water to irrigate the whole orchard at 10% yield potential, then no water was applied to a section of the orchard and production over the next two years would be compromised.

Using the rules outlined above, the areas of the orchard irrigated at 100, 90 and 10% yield potential and receiving no water at the different irrigation water allocations are shown in Table 15. The drought tolerance of olive plant is expressed through lower water requirements at low production levels, and in this scenario it allows a larger area of the orchard to be maintained at a higher level of production (Table 15). For example, at 30% irrigation allocation, 12 ha of the citrus orchard received no water so produced no product. By comparison, at 30% water allocation in the olive orchard, 20 ha of the orchard could be maintained at 90% yield potential.

The water use efficiency ($/ML irrigation water) of irrigating citrus and olive orchards at different irrigation water allocations is presented in Figure 21, based on the irrigation areas in Table 15 and the yield and price assumptions outlined. At 90 to 100% irrigation allocations the water use efficiency of both crops is similar however the olive orchard is considerably more water use efficient at lower irrigation allocations. The water use efficiency of the olive orchard is stable at low irrigation allocations because the olive tree has a

<table>
<thead>
<tr>
<th>Water allocation (%)</th>
<th>Area irrigated at each yield potential (ha)</th>
<th>Total water used (ML/orchard)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100%</td>
<td>50</td>
<td>320</td>
</tr>
<tr>
<td>80%</td>
<td>42</td>
<td>256</td>
</tr>
<tr>
<td>60%</td>
<td>22</td>
<td>192</td>
</tr>
<tr>
<td>30%</td>
<td>38</td>
<td>96</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Water allocation (%)</th>
<th>Area irrigated at each yield potential (ha)</th>
<th>Total water used (ML/orchard)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100%</td>
<td>50</td>
<td>345</td>
</tr>
<tr>
<td>80%</td>
<td>10</td>
<td>276</td>
</tr>
<tr>
<td>60%</td>
<td>40</td>
<td>207</td>
</tr>
<tr>
<td>30%</td>
<td>20</td>
<td>104</td>
</tr>
</tbody>
</table>
low water requirement for low levels of production, which in this analysis can be met by rainfall. By contrast, the water use efficiency of the citrus orchard declines rapidly at irrigation allocations less than 80%. This result is due to the citrus tree having higher water requirements at low levels of yield potential compared to the olive tree (Figure 16).

When the differences in water use efficiency are examined on a whole of orchard basis, the gross farm income of both the olive and citrus orchards declines as less irrigation water is available but the decline is more rapid for citrus (Figure 22).

Using the gross values of irrigation in $ per ML of irrigation applied and gross farm income (Figure 21 and Figure 22), together with the irrigation allocations over the last 10 years in the Goulburn Broken catchment (Figure 20), the average annual gross value of production per ML of irrigation water applied was $1,342/ML for citrus and $1,694 for olives, and the average annual gross farm income was $384 and $445 thousand respectively. This represents a 26% increase in the value of production per ML irrigation water applied, and a 15% increase in gross farm income over the period.

While these analyses are simplistic, this highlights the potential for resilient irrigated crops to be a valuable component of agricultural systems in future climate scenarios where irrigation water availability is lower and more variable.

Figure 21. Gross value of irrigation in $/ML applied to olive and citrus orchards at different levels of irrigation availability (based on management, production and prices outlined).

Figure 22. Gross farm income from a 50 ha olive or citrus orchard at different levels of irrigation availability (based on management, production and prices outlined).
Dryland Murray-Darling basin and the marginal cropping fringe of southern Australia

Selection criteria

In conjunction with recent trends in water allocation that have seen water traded away from broadacre irrigated agriculture, such as dairy and rice, to higher value horticulture production such as pomefruit and viticulture, reduced water availability will see a conversion of irrigated dairy and rice farms to dryland production systems. Climate projections for the Murray-Darling basin and the marginal cropping fringe of southern Australia indicate that dryland systems will need to be adapted to lower and more variable rainfall patterns, with higher temperatures. Well adapted new rural industries will require the following plant traits:

• Water use efficiency – higher water use efficiency plants will make better use of the available water resources.
• Heat tolerance – to cope with increased frequency of hot days and heatwaves.
• Drought tolerance – the ability to tolerate or avoid drought through the use of seasonal growth patterns or plant characteristics such as deeper root systems.
• Frost tolerance – even with warming, frost is likely to remain an issue in the southern Murray-Darling basin, in part associated with longer dry periods.
• Lower chilling requirements (vernalisation) – warming may reduce the number of cold periods, restricting production of crops that have a vernalisation requirement.

At a regional scale, increasing agrodiversity is suggested as a means of reducing the risk associated with extreme climatic events. It is clear that there will not be one crop or system that meets all of these criteria because some of these plant attributes are complementary (e.g. heat tolerance and low vernalisation requirement) while others not compatible (e.g. heat and frost tolerance). Improvements to agricultural systems management, e.g. by utilising seasonal climate forecasting, will also be important components in adaptation to climate change.

New enterprises

Three specific opportunities are identified where new enterprises can make a significant contribution to resilient and diverse farming systems in warmer and drier dryland farming systems: alternate crops in cereal systems, industrial crops for arid environments, and options for retired cereal country.

The rationale for recommending new rural industries in this region follows the principle of Garnaut (2008), whereby food crops are grown where possible and industrial/energy crops are allocated to land where food can no longer be grown.

Alternate crops in cereal systems

Mustards and Crambe

The mustards, Indian (Brassica juncea) and Ethiopian (B. carinata), are adapted to the climatic zone of the Australian wheat belt. They tolerate water stress, pests and diseases better than canola (B. napus), and tend to have higher yields in low rainfall (<350 mm) environments (Francis & Campbell 2004). Mustard crops are adapted to loam and other fertile soil types, similar to canola. Crambe (Crambe abyssinica) is an industrial oil crop for the medium rainfall zone (Francis & Campbell 2004). Crambe is adapted to both loam and sandy soil types, and it is highly competitive with weeds. At harvesting the seed retains its husk, making transport of the product expensive relative to other oilseeds.

Quinoa

Quinoa (Chenopodium quinoa) is a pseudocereal that produces a gluten-free grain with higher protein and fibre content than cereals. It is adapted to the 250-380 mm rainfall zone, has a short growing season and is tolerant to drought, frost and salinity stresses (Vinning & McMahon 2006). An RIRDC-funded research project examining its growth characteristics in Australia is currently being conducted by Jon Clements at the University of Western Australia.
Tepary bean

Tepary bean (*Phaseolus acutifolius*) is a short duration summer food crop (Hamama & Bhardwaj 2002) that is native to regions with less than 400 mm annual rainfall in south-western USA and Mexico. It is drought and heat tolerant (Debouck 1994) and can reach maturity after a single rainfall or irrigation event of sufficient quantity due to its short growing season (Table 16). The tepary bean has not been extensively developed in the USA because the availability of cheap irrigation water has allowed production of other beans (e.g. *P. vulgaris*, kidney bean). However, the tepary bean is more drought tolerant than other beans, and performs better than other beans when no irrigation is applied. Limitations include the plant’s small seed size that makes harvesting difficult.

Native grass crops

Native grass species are adapted to low and irregular rainfall and high temperatures, thus should be suited to future climate scenarios. There is potential to use native grasses, such as weeping grass (*Microlaena stipoides*), as dual purpose crops, i.e. to harvest for grain in good years and use as a forage source for grazing animals in poorer years. Ian Chivers (Native Seeds Pty Ltd) is currently working on this in a RIRDC funded project, and has identified a number of other species with potential, including shot grass (*Paspalidium globoideum*), wheat grass (*Elymus scaber*) and channel millet (*Echinochloa turneriana*).

Other species which may be worth considering as alternate crops in cereal systems include Chickpea (*Cicer arietinum*), Chinese mustard greens or gai choy (*Brassica juncea*), Cowpea (*Vigna unguiculata*), Grain amaranth (*Amaranthus spp*), Mizuna (*Brassica juncea*), Moth bean (*Vigna aconitifolia*), Snap beans (*Phaseolus vulgaris*) and Yard-long asparagus bean (*Vigna unguiculata subsp sesquipedalis*).

Table 16. Selected cultivated species of *Phaseolus*: daytime temperature range, mean annual precipitation, duration of growth cycle from start to end of harvest, yield potential in tropical areas.

<table>
<thead>
<tr>
<th>Species</th>
<th>Temperature (°C)</th>
<th>Precipitation (mm/year)</th>
<th>Growth cycle (days)</th>
<th>Yield (t/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tepary bean</strong></td>
<td>20–32</td>
<td>200–400</td>
<td>60–110</td>
<td>0.4–2.0</td>
</tr>
<tr>
<td><em>P. acutifolius</em></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Other Phaseolus species</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>P. coccineus</em></td>
<td>12–22</td>
<td>400–2600</td>
<td>90–365</td>
<td>0.4–4.0</td>
</tr>
<tr>
<td><em>P. lunatus</em></td>
<td>16–26</td>
<td>0–2800</td>
<td>90–365</td>
<td>0.4–5.0</td>
</tr>
<tr>
<td><em>P. polyanthus</em></td>
<td>14–24</td>
<td>1000–2600</td>
<td>110–365</td>
<td>0.3–3.5</td>
</tr>
<tr>
<td><em>P. vulgaris</em></td>
<td>14–26</td>
<td>400–1600</td>
<td>70–330</td>
<td>0.4–5.0</td>
</tr>
</tbody>
</table>

Source: Debouck (1994).
Industrial crops for arid environments

**Guayule**

Guayule (*Parthenium argentatum*) is a small perennial shrub native to central Mexico and south-west USA. It produces a natural rubber product (Thompson 1990) that has a significant advantage over rubber from *Hevea brasiliensis* for use in latex products (e.g. medical gloves) because it does not cause the life-threatening Type 1 latex allergy (George et al. 2005). Harvesting the rubber involves clipping plant tops (roots also contain rubber and can also be harvested) every 2-3 years. Plant improvement is currently being undertaken by the United States of America Department of Agriculture (USDA) and the Arid-land Agricultural Research Centre in Arizona.

A RIRDC funded project has evaluated USDA guayule lines in south-east Queensland, with the more recent lines showing improved yields (George et al. 2005). Climatically, the plant appears to be well suited to the semi-arid regions of Australia with summer-dominant rainfall patterns, but needs 325 mm annual rainfall for dryland production or supplemental irrigation. Guayule cannot tolerate waterlogging, but can withstand long periods of drought (George et al. 2005). Considerable potential still exists to improve yields through selection of better adapted guayule lines, and more research is required to develop agronomic practices, and effective seed harvesting and processing techniques (George et al. 2005).

**Lesquerella**

Lesquerella (*Lesquerella fendleri*) is a member of the Brassicaceae family. It is a perennial plant that is native to arid areas in south-west USA and Mexico. Lesquerella produces a vegetable oil rich in hydroxyl fatty acids for use in lubricants and cosmetics, as a replacement for castor oil (Dierig 1995), and potentially as a biofuel source (Kish 2008). Although the plant is a perennial, it is often cultivated as a winter-growing annual crop for temperate arid regions with 250-400 mm annual rainfall (Dierig 1995). In south-western USA the crop is planted in October and harvested in June, and responds to fertiliser and irrigation (Dierig 1995). Lesquerella is best suited to well-drained soils. Plant improvement is currently being undertaken by the USDA at the Arid-land Agricultural Research Centre in Arizona, including the release of a salt-tolerant line (Kish 2008). Recent research has involved improving cultivation practices, such as developing weed control programs (Foster et al. 2007).

**Buffalo gourd**

Buffalo Gourd (*Cucurbita foetidissima*) is an arid-land industrial crop identified by Thompson (1990) as having economic potential. Buffalo gourd is a source of vegetable oils and protein, and as such must compete with other temperate crops with similar products. Cucurbitacins, which are natural insect attractants and have other potential uses, are a unique product of buffalo gourd that would need to be economically exploited as a medicinal product (Thompson 1990) for this to be an economically feasible cropping option.

**Grindelia**

Grindelia (*Grindelia camporum*) is a herbaceous perennial, indigenous to arid areas of central California. The plant produces significant quantities of extractable diterpene acid resin for industrial applications (Thompson 1990). The crop requires irrigation in arid environments, but its water requirement is less than other crops grown in similar environments. Plant breeding to improve yields is required to make the plant economically competitive (Thompson 1990).

Other species which may be worth considering as industrial crops for arid environments include Cardoon (*Cynara cardunculus*), Chicory (*Cichorium intybus*) and Parsley (*Petroselinum crispum*).
Options for retired cereal country

**Eucalyptus spp.**

There are two main Australian native species (*Eucalyptus polybractea* and *E. radiata* ssp. *radiata*, *cineole variant*) used for cineole-type eucalyptus oil production in Australia (Davis & Bartle 2004). *E. polybractea* is well adapted to drought and low rainfall environments down to 350 mm per annum (Davis & Bartle 2004). Once established, the crop can be more profitable than wheat in dry years, hence has potential in a drier future climate. A major barrier to the industry is the high cost of establishing trees and processing compared with cheaper production systems in China. The future of the industry hinges on large scale production at lower prices, or finding additional uses for the plantations which can support the high cost of establishment, e.g. as a carbon sequestration option for low rainfall environments in a future carbon constrained economy.

**Animal industries**

A return to grazing industries is predicted in areas that become too hot and dry for continued cereal cropping, and there may be opportunities for goat and kangaroo industries in the more arid environments. Goats have an advantage over sheep and cattle in more arid environments because they select (browse) from a wider range of plants, so have better survival on poor quality pastures and also can graze further from water points (Bruce McGregor, pers comm.). Goats also provide weed control.

The kangaroo produces significantly less methane than sheep or cattle and therefore the kangaroo industry would be advantaged in a future scenario where agriculture was included in an emissions trading scheme by producing less emission per unit of meat (Wilson & Edwards 2008). Kangaroos are well adapted to arid environments where other options are limited. They generally have a low impact on the environment as they move to find food. Garnaut (2008) concluded that kangaroo meat could become an important industry in a carbon constrained economy but significant issues need to be addressed, including livestock and farm management issues, consumer attitudes, and the generally slow pace of change in consumer food preferences.
Northern Australia

Selection criteria

Northern Australia is potentially less affected by climate change than the other regions analysed because there is no clear signal for increased or decreased rainfall, whereas substantial decreases in rainfall are predicted for the southern Australian regions. In addition, the development of new irrigation resources is proposed for some areas of northern Australia (e.g. stage 2 of the Ord River irrigation scheme; NRETAS 2007a), indicating that existing industries could continue to operate if climate change occurred as predicted. The tendency for the range of new rural industries suited to northern Australia to be unaffected by projected climate change is also supported by PLANTGRO simulations, where there was no change in the performance of most new crop species (see following chapter).

However, while water inputs to this region may not change greatly, they will need to be managed carefully. Increased temperatures, and consequently, increased evaporation, are predicted for this region. These climatic factors, together with extremely low winter rainfall, highlight the importance of water use efficiency in new crops. There is also increasing recognition of the importance of reserving some flows from potential irrigation supplies for natural ecosystems (e.g. the Tindall Limestone Aquifer - Katherine water allocation plan; NRETAS 2007b), which will reduce the supply of irrigation available for agriculture.

Important plant characteristics for new rural industries in Northern Australia may include:

- Heat tolerance – to cope with increased general temperatures, and the increased frequency of hot days and heatwaves.
- Lower chilling requirements (vernalisation) – warming may reduce the number and degree of cold periods, restricting the production of crops that have a vernalisation requirement. However, the production period for crops limited by cold weather may be extended as winters become warmer.
- Water use efficiency – higher water use efficiency plants will make better use of the available water resources. If irrigation is not available, plants need to be adapted to extended wet and dry periods (e.g. native plants and those introduced from similar climates).
- Wind/storm tolerance – to cope with more intense tropical cyclones. Suitable plant characteristics may include low-growing perennials, annual plant systems because these can be rapidly replaced after damage, and crops that still have a commercial product after suffering damage from extreme weather conditions.

At a regional scale, increasing agrodiversity is suggested as a means of reducing the risk associated both with extreme climatic events, and with new rural industries in which markets are still being developed.

The following new enterprises have been chosen as suitable for production in Katherine region now and under conditions predicted for the future under climate change.

Peanut

Peanut (Arachis hypogaea) production has recently been extended into the Northern Territory and is being trialled in Western Australia (http: www.pca.com.au ). Because of low growth habit and uptake of nutrients directly by pods, crops require friable, well-drained soil free of organochlorine pesticide residues or heavy metals, and careful management of nutrition and weeds. Although peanuts are considered drought tolerant and capable of producing yield in drought, attention to soil moisture reduces the risk of Aflatoxin infection, and improves peanut quality and profitability. Specialised equipment is required. The industry is well organised with markets and agronomic advice available.

Peanuts are a legume species that are best grown in rotation with grass or cereal crops, providing potential to increase agrodiversity. The growing season for peanut in Northern Australia is also suited to current and proposed climate changes as the crop is grown in winter months in northern Australia to ensure that harvesting occurs in the dry season, thus limiting exposure to hot days and wind damage. As a minimum soil temperature of 18 °C is required for germination, predicted temperature increases may provide an opportunity for a greater range of planting dates to take advantage of the higher rainfall outside of winter months and thus reduce reliance on irrigation water.
Watermelon

Watermelons (*Citrullus lanatus*) are sold fresh or juiced (www.pmgagriculture.com.au). They grow best in hot, humid climates and can adapt to a variety of soils (www.seedless.com.au), but need irrigation. Watermelon production has expanded into the Northern Territory to enable the growing season (winter) to extend 13 weeks beyond that at Condobolin, in central west New South Wales (www.pmgagriculture.com.au).

Pomegranate

Pomegranates (*Punica granatum*) are large shrubs/small trees. Fruit provides a range of health benefits (www.pmgagriculture.com.au), and is sold as fresh whole fruit or arils separated from the fruit, and as juice (www.lewishorticulture.com.au/pomegranates). Young trees (60 to 100 cm high) begin to bear well three to four years after planting. Plants tolerate a wide range of soil types, drought and brief waterlogging, but wind protection is beneficial (www.agric.wa.gov.au/PC_92669.html?s=1001). Production in northern Australia enables the production period to be extended beyond that in southern Australia (www.pmgagriculture.com.au).

Kenaf

Kenaf (*Hibiscus cannabinus*) is an annual or biennial plant grown mainly for its fibre (stalks), although oil can also be extracted from its seed. It grows during the wet season and is harvested during the dry season, which may also suit it to dryland production in northern Australia (http://www.agripulp.com/econ.html#kenaf). It tolerates drought and a range of soil types. Commercial production has been limited by the lack of pulp mills for making paper since this industry is geared up to use wood (http://www.newcrops.uq.edu.au/newslett/ncn10212.htm). Research is also being undertaken to develop mechanised harvesting, and methods of compacting or partially processing the fibres on-site to reduce transport costs (Jobling 2004).

Bitter melon

Bitter melon (*Momordica charantia*) is a trellised vine-fruit that thrives in hot and humid climates on well-drained soils (http://bittermelon.org/grow/farmgrowinginformation). It is sold fresh for Asian cooking. It is intolerant to flooding, and in northern Australia it is grown in winter with irrigation (https://rirdc.infoservices.com.au/downloads/02-134.pdf). First fruit can be harvested around 70 days after planting, and every two to three days afterwards (Gosbee 2004). Care is required to harvest the fruit before it is physiologically mature and to place it in cool storage to slow further ripening.

Sesame

Sesame (*Sesamum indicum*) is an annual crop grown for its seed and seed oil (Bennett 2004). Temperature and day length responses indicate that it is suited to wet season production in northern Australia where it can be largely rainfed, but good drainage is essential as it is extremely sensitive to waterlogging. It is capable of producing good yields under high temperatures. However, it is sensitive to lodging (and possibly shattering) in strong winds as the crop matures, which may reduce yields. It can be grown in rotation with other crops such as legumes, thus contributing to farm agrodiversity.

Burdock

Burdock (*Arctium lappa*) is grown as an annual plant for its long tap root, which is exported fresh, frozen or dried (Nguyen 2004). Greatest profitability is in the potential to supply burdock to Japan in its off-season between January and June. While burdock grows best at 20-30°C, it tolerates much higher temperatures if there is high humidity, which is predicted to occur under climate change. Roots grown for fresh markets are 60-90 cm long, so soils should be sandy and cultivated to the full depth of root growth to avoid forking.
Guar

Guar (Cyamopsis tetragonoloba) is a tropical summer grain legume grown for the vegetable gum contained in its seed, which is widely used in the food and a wide range of other industries (Douglas & Routley 2004). Guar is deep rooted which enables it to tolerate dry conditions. It is also tolerant of high temperatures (35-40°C maximums are ideal). Crops are produced in summer months and can provide soil nitrogen for subsequent crops. As excess water increases vegetative growth and lowers harvest index, deep, well-drained soils are required. Guar can be useful in crop rotations and thereby contributes to agrodiversity. Marketing studies are underway by RIRDC.

Other species which may be worth considering as crops for Northern Australia include Celeriac (Apium graveolens), Chard (Beta vulgaris var cicla), Eggplant (Solanum melongena), Endive (Chicorium endivia), Fennel (Foeniculum vulgare), Globe artichoke (Cynara scolymus), Jerusalem artichoke (Helianthus tuberosus), Pineapple (Ananas comosus), Purslane (Portulaca oleracea), Rockmelon (Cucumis melo), Saskatoon berry (Amelanchier alnifolia), Society garlic (Tulbaghia violacea), Warrigal greens or New Zealand spinach (Tetragonia tetragonioides) and Winter melon (Benincasa hispida).

Constraints to new rural industries

Each of the industries highlighted above has the potential to produce a product of value, or replace an existing product, and hence has been deemed to have economic potential. One significant advantage with Northern Australia will be the counter-seasonality of production.

The difficulties with the establishment of these new rural industries for future climates, as described in the resilient irrigated, dryland Murray-Darling basin/marginal cropping fringe of southern Australia and the future Northern Australia scenarios, are summarized below:

• The high costs of establishing any crop diversification program (Jackson et al. 2009). These investment decisions have added complexity because they must be made in a period of lower certainty about irrigation water availability.

• The cost of investment in new machinery, processing infrastructure, transport and storage, suited to the new rural industries.

• The lack of tools for predicting the economic bases of these industries, since there are many factors, including projections of production, costs and prices into the future. More detailed economic analyses are required on an industry basis.

• The development of new knowledge and skills for managing the new rural industries, and the retraining of the relevant staff, requiring continued investment in research and development for these new rural industries.

• Unforeseen production difficulties such as the potential weedy ness of new plant species and pest/disease issues. Extensive application of research and development will be required to bring these new rural industries to economic fruition in Australian conditions.
Modelling adaptation of plant industries to future climates

Introduction

Australian agricultural systems encompass a complex, interacting combination of soils, plants, management techniques and climates. The addition of climate change to these systems makes it increasingly difficult to operate successful agricultural businesses because Australian climates are not only highly variable but are also changing, and information about the plants that can grow well in these environments is not fully developed. Computer models that can incorporate the variability and interactions involved in these systems can therefore be useful for predicting the response of plant growth to this suite of environmental and physical factors.

PLANTGRO (v3.01 with batch functionality) is a modular computer program for making coarse predictions of the growth of plants, in terms of limitations to growth within a given soil-climate environment (Hackett 1991). It is highly suited for the objective of identifying possible new enterprise options that could be viable in areas where new rural industries are required due to climate change (see Objectives Chapter) because it has many pre-existing plant input files for new crops whereas detailed models do not exist for many new crops. The diversity of plants included within the program is critical for evaluating alternative agricultural options for future climates (Cavagnaro et al. 2006). Coarse-level predictions of the general limitations to plant growth occurring within a soil-climate environment are made because PLANTGRO uses a system of notional relationships between the plant and its environment. This generality enables users to rapidly determine whether the growth of a plant in an environment will be very good, only average or will result in plant death. This approach also permits plant modules to be modified based on expert opinion in addition to more formal sources of data, which is particularly useful for new plants having relatively little published information suitable for setting up a detailed model. In any case, greater accuracy (in terms of plant productivity) may be difficult to achieve given the uncertainty surrounding both the extent of climate change and the performance of new crops.

The PLANTGRO model and approach

The response of each plant to climate change was determined by comparing its response to the current climate, with the plant response in the projected climates for 2030 and 2070. The effect of climate change on plant growth was simulated for the locations of Emerald (north-east Australia), Goondiwindi (Murray-Darling basin), Katherine (northern Australia), Kyabram (Murray-Darling basin), and Merredin (marginal cropping fringe in southern Australia). These sites were selected for analysis because they were of particular interest to attendees of the workshop conducted to identify New rural industry opportunities (see Approaches to identifying New rural industry opportunities in Methodology chapter). Each simulation requires that a climate, soil, and plant file be selected, to generate a prediction of plant performance in those conditions.

Climate input files

PLANTGRO climate files require monthly data for average total rainfall and evaporation, day length, solar radiation, average maximum and minimum temperature, absolute minimum temperature, and wind speed (Hackett 1991) for each location simulated (Table 17). All values other than wind speed were summarised from daily historical climate information obtained from the Bureau of Meteorology SILO database (http://www.nrweqld.gov.au/silo/ppd/, Jeffery et al. 2001). Data from 1961-1990 were used to estimate values for current climates, and also provided base line data for the prediction of 2030 and 2070 climates using the approach described in the Climate Data and Climate Change Projections section of the Methodology chapter. Evaporation predicted for 2030 and 2070 was based on the changes estimated for the nearest capital city (CSIRO & BoM 2007). Solar radiation and the minimum, maximum and lowest temperature used in this file provide input to plant response relationships described in plant input files.

Soil input files

The factors included in soil input files for PLANTGRO (Table 18) impact on plant growth in different ways. The effects of factors that impact directly on plant growth, such as pH, are included in relationships specified in each plant input file. Other factors, such as water holding capacity, impact on plant growth indirectly and are used to determine the soil water balance. A loam soil without chemical or physical limitations (Table 18) was created for PLANTGRO simulations in order to restrict the influences on plant growth predictions to those of the climate change only. Real soil limitations are assumed to be overcome through management practices, such as fertiliser application to improve soil fertility or lime application to reduce soil acidity.
Table 17. Factors included in climate files (Hackett 1991) and method of determination

<table>
<thead>
<tr>
<th>Factor</th>
<th>Explanation</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar radiation</td>
<td>Average solar energy per day for the month (MJ/m²/day)</td>
<td>Calculated from SILO (Jeffery et al. 2001)</td>
</tr>
<tr>
<td>Maximum and minimum</td>
<td>Average of the daily maximum and minimum temperatures, respectively, for</td>
<td>Calculated from SILO (Jeffery et al. 2001)</td>
</tr>
<tr>
<td>temperature</td>
<td>the month (°C/day)</td>
<td></td>
</tr>
<tr>
<td>Lowest temperature</td>
<td>Lowest minimum temperature likely during the month (minimum °C/month).</td>
<td>Calculated from SILO (Jeffery et al. 2001)</td>
</tr>
<tr>
<td></td>
<td>All temperatures are used to calculate heat energy received by plants,</td>
<td></td>
</tr>
<tr>
<td></td>
<td>estimate heat and cold damage to plants, and drive the development of</td>
<td></td>
</tr>
<tr>
<td></td>
<td>plants through their growth phases.</td>
<td></td>
</tr>
<tr>
<td>Latitude, day length</td>
<td>Day length influences initiation of plant organs</td>
<td>Calculated by PLANTGRO from latitude</td>
</tr>
<tr>
<td>Average wind speed</td>
<td>Reduces chance of frost damage</td>
<td>Commonly used (2 m/s)</td>
</tr>
<tr>
<td>Rainfall</td>
<td>Total rainfall for the month (mm/month)</td>
<td>Calculated from SILO (Jeffery et al. 2001)</td>
</tr>
<tr>
<td>Evaporation</td>
<td>Total evaporation from a Class A pan for the month (mm/month)</td>
<td>CSIRO and BoM 2007</td>
</tr>
</tbody>
</table>

Table 18. Factors included in PLANTGRO’s soil input files (Hackett 1991), and the values selected to provide a soil that did not limit plant growth

<table>
<thead>
<tr>
<th>Factor</th>
<th>Explanation</th>
<th>Value (PLANTGRO remarks)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aeration</td>
<td>Availability of oxygen to roots most common during year</td>
<td>Class 6 – well aerated</td>
</tr>
<tr>
<td>Base saturation</td>
<td>% CEC, which relates to chemical ions of valued to plant growth</td>
<td>70 % CEC (good agricultural soil)</td>
</tr>
<tr>
<td>CEC</td>
<td>Ability of soil to retain cations against leaching</td>
<td>35 cmol (+)/kg (good agricultural soil)</td>
</tr>
<tr>
<td>Depth</td>
<td>Depth of soil penetrable by roots</td>
<td>2 m (good agricultural soil)</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>Major nutrient for plant growth</td>
<td>0.6 % (well fertilised soil)</td>
</tr>
<tr>
<td>pH</td>
<td>Measure of soil acidity alkalinity affecting nutrient/toxin availability</td>
<td>6.5</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>Major nutrient for plant growth</td>
<td>25 ppm (Olsen techniques; well fertilised soil)</td>
</tr>
<tr>
<td>Potassium</td>
<td>Major nutrient for plant growth</td>
<td>0.6 cmol (+)/kg (well fertilised soil)</td>
</tr>
<tr>
<td>Salinity</td>
<td>Harmful to most crops</td>
<td>0 dS/m (lower end of usual agricultural limit)</td>
</tr>
<tr>
<td>Slope</td>
<td>Refers solely to plant stability rather than access</td>
<td>0°</td>
</tr>
<tr>
<td>Texture</td>
<td>Affects infiltration and ability of roots to lengthen.</td>
<td>4 (loam)</td>
</tr>
<tr>
<td>Available water holding capacity %</td>
<td>Amount of water held in soil after it has been freely drained, and is extractable by plants</td>
<td>16 % cm/m (loam)</td>
</tr>
<tr>
<td>Drainable water capacity %</td>
<td>Amount of water which drains freely from saturated soil (usually from large soil pores)</td>
<td>16 % cm/m (loam)</td>
</tr>
</tbody>
</table>

(CEC, cation exchange capacity)

Plant input files

PLANTGRO 3.01 includes over 1800 plant input files, including files for many new crops included in the RIRDC’s New Crop Industries Handbook (Salvin et al. 2004). Plant input files can be in a phasic format which describes plant responses according to growth phases, or in a briefer format when less is known about the plant (Hackett 1991). Input files available for the new crops included in PLANTGRO followed the general format, reflecting the novelty of these crops. The default form of these plant files was used to predict plant response to climate change.

Plant input files describe the plant’s response to factors from the climate and soil input files (Table 17, Table 18) in terms of notional x,y relationships. In these relationships, the effect of a factor such as pH is assigned a value between 0 and 9 according to its effect on crop performance. The plant response to each of these factors forms the output file described below.

Output files

PLANTGRO provides an output file describing plant performance for each plant-soil-climate combination. Plant performance in response to each environmental factor, is provided in terms of limitation ratings (LR). As a percentage of maximum performance, LR 0 = 100, LR 2 = 75, LR 4 = 50, LR 6 = 25 and LR 8 and LR 9 = 0, where LR 8 = slow death and LR 9 = rapid death. However, high limitation ratings
may not be lethal if they can be overcome with management. Single limitation ratings were reported by PLANTGRO for the response of plants to soil factors, while monthly limitation ratings were reported for climatic factors.

The performance of most plants was limited by several soil and climate factors, of varying severity in different months. An additional factor reported by PLANTGRO is the length of growing season, which refers to the length of time required for the plant to mature to harvestable age under conditions prevalent during that month. However, to reduce the complexity of the limitations reported by PLANTGRO and focus on the effect of climate change on plant growth, limitation factors for soil properties were ignored as it was assumed that these could be overcome with management. The response of plants to climate change in any prediction year was therefore summarised by identifying either (1) the most limiting climatic factor in any month (day length effects on plant clock or for management purposes, solar radiation, brief cold, extended cold, heat damage, water availability, seasonal water logging, flooding, and wind damage), or (2) where crop death was predicted to occur before the end of the growing season.

The response of each crop to climate change was summarised by classifying the crop based on changes in its most limiting factor over time. The performance of the crop in the region now and in response to climate change therefore resulted in the classification presented in Table 19.

An example of the summary simulation results for garlic (Allium sativum L.) identifies water availability, length of growing season, and brief cold as limitations at the different locations simulated (Table 20). In terms of suitability for a location, water availability is disregarded as a limitation because it was assumed that irrigation would be available to supplement rainfall. Consequently, garlic is suited for production now, and under climate change, in Emerald and Katherine. The length of growing season was too short to enable garlic to be harvested in any climate at Kyabram, and so was unsuited for production in that region. As the climate warms in Goondiwindi and Merredin, length of growing season was replaced by water availability as the greatest limitation rating, and so garlic may provide a new crop opportunity in these locations.

Output files modified following stakeholder consultation

The classification of crop performance in new climates as predicted by PLANTGRO was presented at a workshop held to identify New rural industry opportunities (see Methodology section). The default plant input files for azuki bean, jojoba and date palm were modified following input from workshop attendees (Table 21) and were used to enhance predictions for crop performance.

Opportunities and threats for new crops identified by PLANTGRO

The classification of simulated plant performance identified many currently suited crops and potential new crops able to grow after changes in climate (Table 22 to Table 26), which were typically greater in number than either crops that had declining production, or were unsuited for production. However, while the classification system enabled the suitability of new crops to be conveniently summarised, this classification should be regarded as indicative only due to the limited information available for new crops (Hackett 1991). This is particularly so for annual crops, as the most severe monthly limitation used for classification may not be relevant for the period in which the crop is grown (e.g. brief cold may not be relevant for summer crops). This classification may also not account for the seasonal requirements of some crops. For example, date palm is suited for growth in all climates, but date fruit actually requires a hot dry summer and so Katherine is not suitable for commercial date production. Consequently, it is also important to consider the complete simulation results, together with knowledge of crop requirements.

Predictions in general show that climate change resulted in new crop opportunities in southern Australian locations. These occur because crop limitations such as excessive cold and short growing seasons are replaced by water limitations, for which irrigation is assumed to be available. As tropical crops are currently suited to northern Australia, climate change did not result in as many new crop opportunities for this region.

Table 19. Classification scheme for crops based on changes to limitation ratings in 1990, 2030, and 2070

<table>
<thead>
<tr>
<th>Suitied for the region under new climate</th>
<th>Yes</th>
<th>Currently growing in the region</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yes</td>
<td>New crop opportunity</td>
<td></td>
</tr>
<tr>
<td>e.g. plants limited by cold in 1990, but limited by water availability in later years</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maybe</td>
<td>More detailed assessment</td>
<td></td>
</tr>
<tr>
<td>e.g. change in management or genetics may be necessary to make plant more suitable to environment</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No</td>
<td>No change: unsuited all climates</td>
<td></td>
</tr>
<tr>
<td>e.g. plants that are never suited to the climate because they die before the growing season is too short</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 20. The factor with the greatest limitation rating affecting the simulated growth of garlic (*Allium sativum* L.) in climates in 1990, 2030, and 2070 (0, no limitation; 9, rapid death)

<table>
<thead>
<tr>
<th>Location</th>
<th>Most limiting crop factor (value)</th>
<th>Crop classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emerald</td>
<td>Water availability</td>
<td>Suited all climates</td>
</tr>
<tr>
<td>Goondiwindi</td>
<td>Length of growing season</td>
<td>New crop opportunity</td>
</tr>
<tr>
<td>Katherine</td>
<td>Water availability</td>
<td>Suited all climates</td>
</tr>
<tr>
<td>Kyabram</td>
<td>Length of growing season</td>
<td>Unsuited all climates</td>
</tr>
<tr>
<td>Merredin</td>
<td>Length of growing season</td>
<td>New crop opportunity</td>
</tr>
</tbody>
</table>

Table 21. Change in notional x (limitation), y (suitability rating) relationships for plant input files for azuki bean (*Vigna angularis* (Willd.) O.), date palm (*Phoenix dactylifera* L.) and jojoba (*Simmondsia chinensis* Link.) following input from workshop

<table>
<thead>
<tr>
<th>Limitation</th>
<th>Limits of values in notional relationship between limitation and suitability</th>
<th>Comments from industry</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Original values</td>
<td>Modified values</td>
</tr>
<tr>
<td>Day length</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>Brief cold (°C)</td>
<td>-4</td>
<td>-1</td>
</tr>
<tr>
<td>Extended cold (°C)</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>Heat damage (°C)</td>
<td>39</td>
<td>42</td>
</tr>
<tr>
<td>Thermal units (°C)</td>
<td>8, 22, 32</td>
<td>10, 25, 35</td>
</tr>
<tr>
<td>Seasonal waterlogging (days)</td>
<td>0</td>
<td>20</td>
</tr>
<tr>
<td>Flooding (days)</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>Brief cold (°C)</td>
<td>10</td>
<td>13</td>
</tr>
<tr>
<td>Extended cold (°C)</td>
<td>14</td>
<td>17</td>
</tr>
</tbody>
</table>

(*Suitability 0, unsuited for crop growth; suitability 9, highly suited for crop growth*)
Table 22. Preliminary classification of crops according to simulated performance in response to climate change over 1990, 2030, and 2070, at Emerald (north-east Australia region)

<table>
<thead>
<tr>
<th>Suited for the region under new climate</th>
<th>Currently suited to the region</th>
<th>No</th>
</tr>
</thead>
</table>
| Yes                                    | No change: suited all climates | Yes | New crop opportunity
| No                                     | Decline in production          | No change: unsuited all climates
| German camomile, Globe artichoke, Horehound |

Table 23. Preliminary classification of crops according to simulated performance in response to climate change over 1990, 2030, and 2070, at Goondiwindi (Murray-Darling basin region)

<table>
<thead>
<tr>
<th>Suited for the region under new climate</th>
<th>Currently suited to the region</th>
<th>No</th>
</tr>
</thead>
</table>
| Yes                                    | No change: suited all climates | Yes | New crop opportunity
| Applemint, Basil, Chinese cabbage, Coriander, Crambe, Cumin, Dill, Eddoe, Globe artichoke, Kenaf, Leaf mustard, Lima bean, Parsley, Peppermint, Chinese radish, Rat-tailed radish, Western radish, Ramie, Roselle (altissima), Stevia, White mustard |
| Maybe                                  | More detailed assessment      | More detailed assessment |
| Calendula, European pennypoyal, Fenugreek, Prickly wattle, Quandong, Valerian, Watermelon, York gum |
| No                                     | Decline in production         | No change: unsuited all climates
| Azuki bean, American ginseng, Bitter gourd, Cardamom, Cashew, Chinese water chestnut, Citronella grass, Cluster bean, Date palm, Lychee, Malabar lemongrass, European olive, Pomegranate, Pumpkin, Quandong, Rambutan, Red clover, Red raspberry, Ridged gourd, Rosemary, Rumex crispus, Saffron, Sage, Sesame seed, Sisal, Smooth lufa, Soyabean, Spearmint, Squash gourd, Sunn hemp, Sweet balm, Sweet pepper, Thyme, True lavender, Valerian, Waabo, West Indian lemongrass |
### Table 24. Preliminary classification of crops according to simulated performance in response to climate change over 1990, 2030, and 2070, at Katherine (northern Australia region)

<table>
<thead>
<tr>
<th>Suited for the region under new climate</th>
<th>Currently suited to the region</th>
<th>New crop opportunity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yes</td>
<td>Yes</td>
<td>No change: suited all climates</td>
</tr>
<tr>
<td>Abaca, Azuki bean, Aji, Ambarella, Applemint, Bariála, Barobans, Basil, Bitter gourd, Black walnut, Carambola, Cardamom, Cashew, Chinese cabbage, Chinese water chestnut, Citronella grass, Cluster bean, Coriander, Corn mint, Cumin, Dandelion, Date palm, European hazelnut, False citronella, Fennel, Fenugreek, Garlic, Giant bamboo, Ginger, Hemp, Hot pepper, Jackfruit, Jojoba, Kenaf, Leaf mustard, Lima bean, Longan, Lychee, Malabar lemongrass, Narrow-leafed peppermint, European Olive, Peppermint, Pimentchien, Pomegranate, Prickly wattle, Pumpkin, Quandong, Chinese Radish, Leaf Radish, Western Radish, Rambutan, Ramie, Ridged gourd, Roselle (altissima), Rosemary, Rosha grass v. motia, Rosha grass v. sofia, Sacred lotus, Sesame seed, Smooth luffa, Soyabeans, Spearmint, Squash gourd, Sunn hemp, Sweet balm, Sweet pepper, True lavender, Valerian, Vanilla, Waabo, Watermelon, Wax gourd, West Indian lemongrass, White Jute, York gum</td>
<td>New crop opportunity</td>
<td></td>
</tr>
<tr>
<td>Maybe</td>
<td>More detailed assessment</td>
<td>More detailed assessment</td>
</tr>
<tr>
<td>Anise, Black currant, Calendula, Caper, Cocoyam, Common licorice, Crambe, Eddoe, Goat chilli, Henequen, Linseed, Oregano, Parsley, Rat-tailed radish, Red raspberry, Saffron, Sage, Sisal, Stevia, Thyme</td>
<td>No change: unsuited all climates</td>
<td></td>
</tr>
<tr>
<td>No</td>
<td>Decline in production</td>
<td>No change: unsuited all climates</td>
</tr>
<tr>
<td>Abaca, Azuki bean, Ambarella, Bariála, Barobans, Bitter gourd, Carambola, Cardamom, Cashew, Chinese water chestnut, Christ-thorn, Citronella grass, Cluster bean, Coconut palm (nuts), Cocoyam, Durian, East Indian walnut, False citronella, Garlic, German camomile, Giant bamboo, Ginger, Hot pepper, Jackfruit, Jojoba, Longan, Lychee, Malabar lemongrass, European Olive, Pomegranate, Prickly wattle, Pumpkin, Quandong, Rambutan, Ridged gourd, Rosemary, Rosha grass v. motia, Rosha grass v. sofia, Sacred lotus, Sandalwood, Sesame seed, Smooth luffa, Soyabeans, Squash gourd, Sunn hemp, Sweet pepper, Vanilla, Waabo, Watermelon, Wax gourd, West Indian lemongrass, White Jute, York gum</td>
<td>No change: unsuited all climates</td>
<td></td>
</tr>
</tbody>
</table>

### Table 25. Preliminary classification of crops according to simulated performance in response to climate change over 1990, 2030, and 2070, at Kyabram (Murray-Darling Basin region)

<table>
<thead>
<tr>
<th>Suited for the region under new climate</th>
<th>Currently suited to the region</th>
<th>New crop opportunity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yes</td>
<td>Yes</td>
<td>No change: suited all climates</td>
</tr>
<tr>
<td>American ginseng, Applemint, Chinese cabbage, Crambe, Dill, Parsley, Peppermint, Chinese radish, Rat-tailed radish, Western radish, White mustard</td>
<td>New crop opportunity</td>
<td></td>
</tr>
<tr>
<td>Aji, Anise, Basil, Black currant, Black walnut, Caper, Chives, Common licorice, Coriander, Corn mint, Cumin, Dandelion, Date palm, Eddoe, European hazelnut, Fennel, Globe artichoke, Goat chilli, Hemp, Henequen, Horehound, Kenaf, Leaf mustard, Lima bean, Linseed, Narrow-leafed peppermint, Oregano, Pimentchien, Leaf radish, Ramie, Red clover, Red raspberry, Roselle (altissima), Rumex crispus, Saffron, Sage, Sisal, Stevia, Thyme</td>
<td>No change: unsuited all climates</td>
<td></td>
</tr>
<tr>
<td>Maybe</td>
<td>More detailed assessment</td>
<td>More detailed assessment</td>
</tr>
<tr>
<td>Calendula, European pennyroyal, Fenugreek, Quinoa, Valerian</td>
<td>No change: unsuited all climates</td>
<td></td>
</tr>
<tr>
<td>No</td>
<td>Decline in production</td>
<td>No change: unsuited all climates</td>
</tr>
<tr>
<td>Abaca, Azuki bean, Ambarella, Bariála, Barobans, Bitter gourd, Carambola, Cardamom, Cashew, Chinese water chestnut, Christ-thorn, Citronella grass, Cluster bean, Coconut palm (nuts), Cocoyam, Durian, East Indian walnut, False citronella, Garlic, German camomile, Giant bamboo, Ginger, Hot pepper, Jackfruit, Jojoba, Longan, Lychee, Malabar lemongrass, European Olive, Pomegranate, Prickly wattle, Pumpkin, Quandong, Rambutan, Ridged gourd, Rosemary, Rosha grass v. motia, Rosha grass v. sofia, Sacred lotus, Sandalwood, Sesame seed, Smooth luffa, Soyabeans, Squash gourd, Sunn hemp, Sweet pepper, Vanilla, Waabo, Watermelon, Wax gourd, West Indian lemongrass, White Jute, York gum</td>
<td>No change: unsuited all climates</td>
<td></td>
</tr>
</tbody>
</table>
Table 26. Preliminary classification of crops according to simulated performance in response to climate change over 1990, 2030, and 2070, at Merredin (marginal cropping fringe in southern Australia)

<table>
<thead>
<tr>
<th>Suited for the region under new climate</th>
<th>Yes</th>
<th>Currently suited to the region</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yes</td>
<td>No change: suited all climates</td>
<td>Abaca, Azuki bean, Ambarella, Bariala, Barobans, Bitter gourd, Carambola, Cardamom, Cashew, Chinese water chestnut, Citronella grass, Cocoyam, False citrus, Garlic, Giant bamboo, Ginger, Hot pepper, Jackfruit, Longan, Malabar lemon grass, European olive, Pumpkin, Ridged gourd, Rosemary, Rosha grass v. motia, Rosha grass v. sofia, Sesame seed, Smooth luffa, Soyabeant, Squash gourd, Sunn hemp, Sweet pepper, Vanilla, Waaibo, Watermelon, Wax gourd, West Indian lemon grass, Yorck gum</td>
<td></td>
</tr>
<tr>
<td></td>
<td>New crop opportunity</td>
<td>More detailed assessment</td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>Aji, Anise, Apple mint, Basil, Black currant, Black walnut, Calendula, Caper, Chinese cabbage, Chives, Common licorice, Coriander, Corn mint, Crambe, Cumin, Dandelion, Date palm, Dill, Eddoe, European hazelnut, European pemyroyal, Fennel, Fenugreek, Globe artichoke, Goat chilli, Hemp, Henequen, Horehound, Jojoba, Kena, Leaf mustard, Lima bean, Linseed, Narrow-leaved peppermint, Oregano, Parsley, Peppermint, Pimentchien, Prickly wattle, Quandong, Quinoa, Chinese radish, Leaf radish, Rat-tailed radish, Western radish, Ramie, Red clover, Red raspberry, Roselle (altissima), Rumex crispus, Sage, Sisal, Spearmint, Stevia, Sweet balm, Thyme, True lavender, Valerian, White mustard</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maybe</td>
<td>More detailed assessment</td>
<td>No change: unsuited all climates</td>
<td></td>
</tr>
<tr>
<td>No</td>
<td>Decline in production</td>
<td>American ginseng, Saffron</td>
<td></td>
</tr>
<tr>
<td></td>
<td>More detailed assessment</td>
<td>Christ-thorn, Cluster bean, Coconut palm (nuts), Durian, East Indian walnut, German camomile, Lychee, Pomegranate, Rambutan, Sacred lotus, Sandalwood, White Jute</td>
<td></td>
</tr>
</tbody>
</table>

**Implications**

PLANTGRO provided a useful tool for the objective of identifying possible new enterprise options that could be viable in the selected areas, by lending support to options identified in the literature. Simulations for capers, quinoa, mustards and crambe in Kyabram supported these crops as potential alternative crops within the irrigated southern Murray-Darling basin which were identified from the literature (see New rural industry Opportunities chapter). Similarly, quinoa, mustard, and crambe were suitable crop options for Merredin that were suggested from the literature for the marginal cropping zone of southern Australia.

However, other PLANTGRO predictions were more conservative and rejected some crops compared to the assessment of New rural industry opportunities based on the literature review (olives, pomegranate and quandong for Kyabram), and also compared to comment at the workshop. These differences encouraged discussion, while plant input files (date palm, jojoba and azuki bean) were readily modified to improve predictions. This capacity to easily refine PLANTGRO input files makes it a useful tool for further, more detailed studies of plant limitations in response to climate change. Differences between initial and later simulations highlight the indicative nature of predictions by PLANTGRO (and, potentially, by literature review) for new crops, given the likelihood that plant responses to the environment for new crops are not completely understood. PLANTGRO is therefore a support tool that should be used in conjunction with information about specific plant requirements, when making an assessment of plant suitability for locations in response to climate change.
Implications

Australian agriculture is highly vulnerable to the impacts of the climate changes predicted for the next century, of increasing temperatures, changing rainfall patterns, and changes in the frequency of extreme climatic events. The challenges for the future are not necessarily the same as those faced in the past, e.g. irrigated industries were established in an era of high water availability and are not resilient to lower and more variable irrigation water supplies. A higher frequency of extreme climate events places an additional risk on farm production, and a greater diversity of crops is required to spread the risk of extreme climate events (e.g. heatwaves, storms, frost) on a regional scale.

A hierarchy of increasingly complex options is required to adapt Australian agriculture to the climate change challenge, from adaptation within existing industries to cope with moderate climate change (up to 2°C warming), to increased diversification, and land use transformation to adapt to progressively larger climate change impacts. These new challenges require new solutions and a number of New rural industry options have been highlighted in this report that have a competitive advantage over existing agricultural industries in warmer and drier future environments due to their drought tolerance, salinity tolerance, resilience to low irrigation water availability, and water use efficiency. In addition to using plants that are better adapted to changed climates, the search must also continue for technologies and markets that will support changes in agricultural commodities.

Low rainfall across southern Australia over the last decade has both reduced the amount of irrigation water supplied and increased water prices, presenting an immediate threat to broadacre irrigated agriculture. High value irrigated crops will continue to be grown, but there is an emerging need for resilient irrigated cropping systems (that can tolerate periods of low water availability and rapidly respond when water is available) to cope with lower water supplies. These resilient irrigated crops will give growers flexibility to respond to water availability and water price signals. To build upon the comparison of the citrus and olive production under limited irrigation water scenarios developed earlier in this report, a 10% or greater improvement in the use of low and variable irrigation supplies is achievable. If this 10% improvement in water use efficiency could be applied to one third of the irrigation water available in a 2030 climate, this would be worth $30 million per year by 2030 (based on the gross value of irrigated agricultural production being $1 billion per year now, and a 12% reduction by 2030; Garnaut 2008).

In dryland agricultural systems, increasingly arid conditions require better adapted plants. Without climate change mitigation, by 2100 wheat yield reductions of 25% are predicted across southern Australian wheat-growing regions (Garnaut 2008). The industries highlighted in this report are better adapted to warmer and drier climates and will help to overcome some of the projected losses from these regions.

The search must also continue for plant systems and/or technologies that will provide a transformational change in agriculture to cope with warmer and drier conditions in southern Australia. Plants such as the cacti can offer the potential of an order of magnitude increase in water use efficiency.

Significant research and development challenges exist for the establishment of new rural industries as viable commercial farming systems so greater investment in research and development for new rural industries is warranted.

Recommendations

This project provides the first step in identifying New rural industry opportunities for Australia in response to projected climate change. The recommendation of this report is that the development of new rural industries is an essential component of the adaptation of Australian agriculture to meet the challenge of climate change. New rural industries provide the potential for a transformational shift in adaptation to future climates that adaptation within existing industries appears not to offer. These transformations in land use will be required to adapt Australian agriculture to new challenges including lower and more variable irrigation water availability and more arid climates across southern Australia.

Producers need to consider climate change impacts in their planning decisions. This is particularly important when making long-term investment decisions, such as in perennial horticulture. The climate change projections and opportunities outlined in this report present a number of new options for producers.

The challenge for policy makers is to recognise the role that new rural industries can play in increasing the diversity and resilience of Australian agriculture in a changing climate. There is much research to be done to evaluate the economics of industry options and develop agronomic techniques for Australian conditions. There is a need to enhance the knowledge and tools available to predict the growth and performance of new crops. Significant research and development challenges exist for the establishment of new rural industries as viable commercial farming systems, so greater investment in research and development for new rural industries is clearly warranted.
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This report explores the potential for new rural industries and enterprises to fill land-use opportunities in areas where current agricultural industries may be strongly challenged by future climates. Agricultural regions and industries have been identified where climate change will alter the current mix and determine the plant traits required for future successes.

It brings together climate projections with an assessment of the vulnerability of existing agricultural industries, and suggests possible production opportunities.

Six broad agricultural regions are identified that encompass a range of climates and agricultural production systems across Australia with a literature review on the impacts and adaptation options for mainstream agricultural industries. This information was combined with recent climate and future climate projections to determine the vulnerability of agricultural industries in each of the regions.

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by B. Cullen, P. Thorburn, E. Meier, S. Barlow & M. Howden
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