An overview of climate change adaptation in Australian primary industries – impacts, options and priorities

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Summary & Synthesis

- The recent Intergovernmental Panel on Climate Change Fourth Assessment Report (Hennessy *et al.* 2007; IPCC 2007b) concluded that the agriculture sector in Australia is particularly vulnerable to climate changes, with potential negative impacts on the amount of produce, quality of produce, reliability of production and on the natural resource base on which agriculture depends. This vulnerability requires high levels of adaptive responses.
- The benefits and positive opportunities presented by climate change may start to peak during the initial stages (possibly mid century), but the negative impacts may lag behind, becoming progressively stronger over time and with greater build up of greenhouse gases in the atmosphere. Caution is therefore needed not to underestimate the long-term challenge of climate change based on initial, more moderate experiences.
- This review has identified a number of potential options for Australian agriculture to adapt to climate change. Many of these options are extensions or enhancements of existing activities that are aimed at managing the impacts of existing climate variability and improving the sustainability and efficiency in the use of natural resources.
- However, less than a dozen of these potential adaptation options have been evaluated for their utility in reducing the risks or taking advantage of climate change impacts. Only a couple of adaptations have been evaluated in relation to the broader costs and benefits of their use.
- These few analyses show that practicable and financially-viable adaptations will have very significant benefits in ameliorating risks of negative climate changes and enhancing opportunities where they occur. The benefit to cost ratio of undertaking R&D into these adaptations appears to be very large (indicative ratios greatly exceed 100:1).
- A key recommendation is thus to progress some more adaptation studies which analyse the costs and benefits of implementation of adaptations (including socio-economic aspects as well as potential feedbacks through greenhouse emissions). This R&D needs to be undertaken in a participatory way with industry groups so as to deal effectively with their key concerns, draw on their valuable expertise and also contribute to enhanced knowledge in the agricultural community.
- There will always be uncertainty about future climate change impacts due to highly uncertain levels of future greenhouse emissions; fundamental uncertainty in the science of the global climate system; uncertainty about how specific changes in climate will affect agricultural/ ecological / social systems, and uncertainty in how communities will respond to these changes.
- Uncertainties are greatly compounded by the complexities of scaling down to finer scales, so generalities about broad-scale impacts of climate change are difficult to translate into specific predications for particular management units (farms / properties / marine areas). Instead, risk-based approaches should be used, focusing on the range of plausible impacts that could occur, rather than potentially-misleading 'average predictions'.
- Given this inherent uncertainty, the need is to develop enhanced adaptive capacity in agricultural systems (including socio-economic and cultural/institutional structures) to cope with a broad range of possible changes. Synergies with existing Commonwealth policies such as self-reliance in drought and their supporting programs such as Advancing Australian Agriculture as well as with institutions such as Landcare are needed develop this capacity.
- To cope with uncertainty in projected climate but the certainty of ongoing technological, cultural and institutional change, there is a need to use an active adaptive management approach for adaptation. This requires directed change in management or policy that is monitored, analysed

and learnt from, so as to iteratively and effectively adjust to ongoing climate changes. Such an approach has profound implications for capacity-building, R&D, monitoring and policy.

- Successful adaptation to climate change will need both strategic preparation and tactical response strategies. Adaptation measures will have to reflect and enhance current 'best-practices' designed to cope with adverse conditions such as drought. Adoption of these new practices will require, amongst other things 1) confidence that the climate really is changing, 2) the motivation to change to avoid risks or use opportunities, 3) demonstrated technologies to enable change to occur, 4) support during transitions to new management or new land use, 5) altered transport and market infrastructure and 6) an effective monitoring and evaluation system to learn which adaptations work well, which do not and why.
- Many potential adaptation options are common across industries. These common or cross-industry themes are outlined immediately below. Industry-specific knowledge gaps and priority action areas are summarised in the next table (with more detailed tables provided at the end of each chapter). The final two synthesis tables summarize regional variation in terrestrial and marine climate change impacts.

Adaptation issues common across industries

Table 1.1: Summary of climate change adaptation issues that are shared across primary industries.

Policy
Develop linkages to existing government policies and initiatives (e.g. Greenhouse Gas Abatement Program, Greenhouse Challenge Plus, salinity, water quality, rural restructuring) and into integrated catchment management so as to enhance the capacity to adapt to climate change.
Managing transitions
Develop policies and mechanisms to provide technical and financial support during transitions to new systems that are more adapted to the emerging climate.
Accepting Uncertainty
Enhance capacity for land and marine managers and supporting institutions to deal with uncertainty. Current and future actions will have to be taken based on uncertain regional- / farm-scale predictions and observations of climate changes. Adaptation strategies will need to enhance adaptive capacity by ensuring that rural communities are equipped to cope with a range of possible, but uncertain changes in local climatic conditions.
Communication
Ensure communication of broader climate change information as well as industry-specific and region-specific information as it becomes available.
Climate data and monitoring
Maintain effective climate data collection, distribution and analysis systems to link into ongoing evaluation and adaptation. Monitor climate conditions and relate these to yield and quality aspects to support/facilitate adaptive management. Develop climate projections that can be downscaled so as to be relevant to farm, catchment and coastal scales. Consideration could be given to the introduction of climate change adaptation into Environmental Management Systems.
R&D and training
Undertake further adaptation studies that include broad-based costs and benefits to inform policy decisions. Maintain the research and development base (people, skills, institutions) to enable ongoing evaluation of climate/CO_2/(cultivar, species or land use)/management relationships, and to streamline rapid R&D responses (for example, to evaluate new adaptations or new climate change scenarios). This R&D needs to be developed in a participatory way so that it can contribute to training that improves self-reliance in the agricultural sector and provides the knowledge base for farm-scale adaptation.
Breeding and selection
Maintain public sector support for agricultural biotechnology and conventional breeding with access to global gene pools so as to have suitable varieties and species for higher CO_2 and temperature regimes and changed moisture availability.
Model development and application
Develop further systems modelling capabilities such as APSIM for crops and AussieGrass and GrazFeed for grazing that link with meteorological data distribution services, and can use projections of climate and CO_2 levels, natural resource status and management options to provide quantitative approaches to risk management for use in several of these cross-industry adaptation issues. These models have been the basis for successful development of participatory research approaches that enable access to climate data and interpretation of the data in relation to farmers own records and to analyse alternative management options. Such models can assist pro-active decision making on-farm and inform policy and can extend findings from individual sites to large areas.

Seasonal forecasting
Facilitate the adoption of seasonal climate forecasts (e.g. those based on El Niño and La Niña, sea-surface temperatures, etc) to help farmers, industry and policy incrementally adapt to climate change whilst managing for climate variability. Maximise the usefulness of forecasts by combining them with on-ground/water measurements (e.g., soil moisture, nitrogen, ocean temperature), market information and systems modelling.
Pests, diseases and weeds
Maintain or improve quarantine capabilities, sentinel monitoring programs and commitment to identification and management of pests, diseases and weed threats. Improve the effectiveness of pest, disease and weed management practices through predictive tools such as quantitative models, integrated pest management, area-wide pest management, routine record keeping of climate and pest/disease/weed threat, and through development of resistant species and improved management practices.
Nutrition
Adjust nutrient supply to maintain grain, fruit, fibre and pasture quality through application of fertiliser, enhanced legume-sourced nitrogen inputs or through varietal selection or management action. Note however, that this may have implications for greenhouse emissions (via field-based emissions of nitrous oxide or emissions of CO_2 during manufacture). Any increases in nutrient supply will have to be carefully managed to minimize soil acidification, waterway eutrophication or runoff into estuaries and marine systems.
Water
Increase water use efficiency by 1) a combination of policy settings that encourage development of effective water-trading systems that allow for climate variability and climate change and that support development of related information networks, 2) improve water distribution systems to reduce leakage and evaporation, 3) developing farmer expertise in water management tools (crop models, decision support tools) and 4) enhancing adoption of appropriate water-saving technologies.
Land use/location change and diversification
Undertake risk assessments to evaluate needs and opportunities for changing varieties, species, management or land use/location in response to climate trends or climate projections. Support assessments of the benefits (and costs) of diversifying farm enterprises.
Salinity
Determine the impact of climate change (interacting with land management) on salinity risk (both dryland and irrigated) and inform policies, such as the National Action Plan for Salinity and Water Quality, accordingly.

Industry-specific priorities

Table 1.2: Summary of priorities for climate change adaptation strategies for Australian agriculture sectors based on identified knowledge gaps and other criteria documented in the report. Note that these exclude the cross-industry components listed above.

Grains
Develop further risk amelioration approaches (e.g. zero tillage and other minimum disturbance techniques, retaining residue, extending fallows, row spacing, planting density, staggering planting times, erosion control infrastructure) and controlled traffic approaches.
Development of crop varieties with appropriate thermal time and vernalisation requirements, heat shock resistance, drought tolerance (i.e. Staygreen), high protein levels, resistance to new pest and diseases and perhaps that set flowers in hot/windy conditions.
Alter planting rules to be more opportunistic depending on environmental condition (e.g. soil moisture), climate (e.g. frost risk) and markets.
Provide tools and extension to enable farmers to access climate data at the scale needed for their decisions and analyse alternative management and land use options including in real-time using approaches akin to Yield Prophet™.
Research and revise soil fertility management (fertilizer application, type and timing, increase legume phase in rotations) on an ongoing basis.
Analyse value-chain and regional adaptation options that translate climate scenarios into meaningful quantities for the stakeholders involved and that include technical, managerial, structural and policy adaptations with consideration of interactions with a large range of other stressors, opportunities and barriers.
Cotton
Improve whole farm and crop water use efficiencies by enabling further improvements in water distribution systems (to reduce leakage and evaporation), irrigation practices such as water application methods, irrigation scheduling and utilizing moisture monitoring techniques.
Develop management systems that improve cotton nitrogen use efficiency.
Select varieties with appropriate, heat shock resistance, drought tolerance, higher agronomic water use efficiency, improved fibre quality, resistance to new pest and diseases (including introgression of new transgenic traits).
Provide information to cotton growers on the likely impacts at their business level (downscaling climate change predictions to regional scales).
Maintain R&D capacity, undertake further adaptation studies which include costs/benefits and streamline rapid R&D responses.
Conduct responsible research into the development of cotton systems in northern Australia.
Research the integrated affects of climate change (temperature, CO_2, and water stress) on cotton growth and yield need further analysis.
Conduct research into avoiding resistance of pests (both insects and weeds) through appropriate integrated pest and weed management systems to maintain transgenic technologies.
Enhance capacity to predict and forecast pest issues in relation to climate change and variability.

Rice
Increase water productivity of cropping systems, through continuing efforts to reduce rice water use, consideration of new crops and rotations, irrigation technologies and farm layouts.
Assess cost benefits of investing in more efficient irrigation methods and farm layouts, as a function of soil type and location.
Assess potential for aerobic and alternate-wet-and-dry (AWD) rice culture in Australian environments; investigate potential benefits and limitations; define optimal water management strategies, fertilisation and weed control issues.
Consider cost-benefits of reducing water conveyancing losses both on-farm and in irrigation district.
Use electromagnetic technology (EM31) to better define which soils are suitable for ponded rice production (to reduce drainage losses).
Sugarcane
Improve farming practices, especially precision irrigation, on-paddock water use and off-paddock water quality impacts and the management of increased climate variability through seasonal forecasting.
Promote innovative farming and processing systems that take an integrated and sustainable approach to risk and opportunity across all inputs.
Capitalise bio-energy opportunities and carbon trading potential for value adding, preferably integrated within innovative farming and processing systems to maximise cross industry benefits.
Focus research on sugarcane physiology and plant improvement in varietal characteristics that enhance resilience to climate change, linked to industry adaptation to higher temperatures, reduced water availability, and extreme events. This will also require knowledge of the genetic x environment x management (G*E*M) interactions.
Enhance human capital through building skills and enhance science capability in climate understanding and risk management across the sugarcane industry.
Include climate change considerations in biosecurity management.
Develop an understanding of the global context of climate change impacts on worldwide production, profitability and markets relative to the Australian sugarcane industry.
Viticulture
Change varieties of winegrapes grown in a region in a gradual but timely manner to better suit the projected climate. New ‘longer season’ varieties can be sourced/bred.
Assess the potential for new sites. Incorporate an analysis of chilling requirements. Also consider other factors such as increasing risk of exposure to bushfire smoke at some sites.
Assess vine response to CO_2-induced increased growth. How will this affect vine growth, yield and yield variability, grape quality and water requirements.
Secure water supplies.
Consider management of the inter-row environment with regard to high rainfall events and also potential frost risk.
Consider possible new winemaking demands (smoke taint/ high alcohol), and also winery infrastructure and harvest logistics.
Horticulture
Change varieties of fruit and vegetables so they are phenologically suited for future conditions and re-assess industry location.

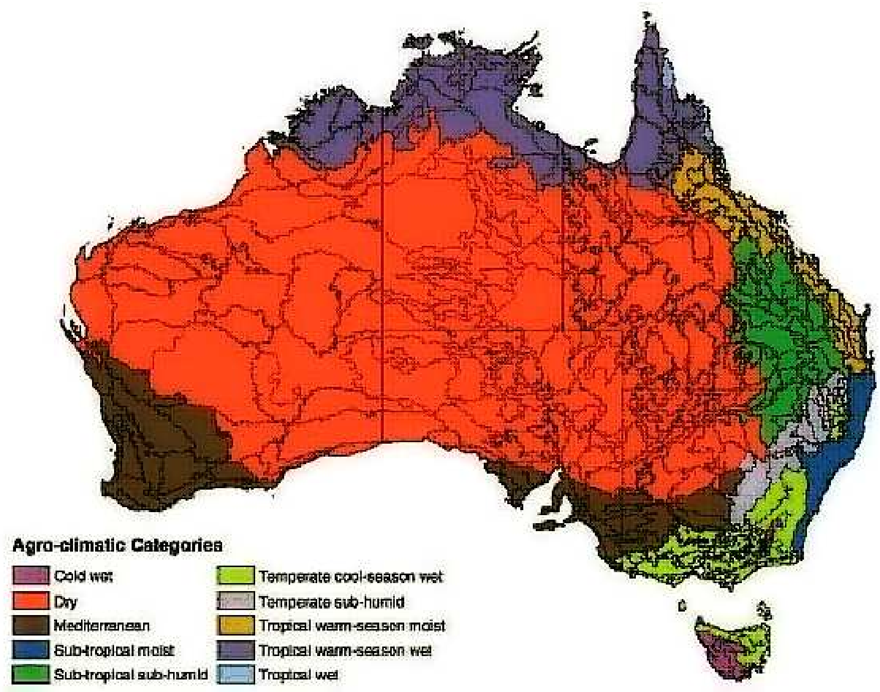
Assess spatial distribution of sites suitable for various horticultural crops, especially with frost likely to reduce in the sub-tropical/tropical regions.
Research on altering crop management and implement breeding programs to avoid adverse crop responses to increasing temperatures.
Determine water access and availability, especially for perennial horticulture.
Assess crop response to enhanced CO_2/ increased temperature.
Forestry
Use bioclimatic analysis to improve knowledge of climatic requirements of particular genotypes and identify vulnerable plantation sites for monitoring.
Evaluate the impacts of high CO_2 and drought risk on tree mortality and establishment strategies. Identify the optimal strategy between high growth (e.g. dense stands with high leaf area) and risk aversion (e.g. sparse stands with low leaf area) for particular sites and particular trees/products.
Develop detailed assessment of drought tolerance of important species and develop drought tolerant genotypes.
Enhance process-based growth models to extend findings on climate change impacts and adaptations from individual sites to large areas. Carry out cost/benefit studies of alternative adaptation strategies.
Develop improved assessments of pest, disease and weed risks as well as appropriate adaptations.
Develop improved assessments of bushfire risks as well as appropriate adaptations.
Grazing
Promote and enhance use of seasonal forecasts in grazing management, and incorporate considerations of projected trends in climate change.
Quantify the range of plausible impacts that uncertain climate change could bring for the grazing industry to clearly define the adaptation challenge.
Determine how pastoralists and policy makers are most likely to respond to climate change impacts and comprehensively evaluate the costs, benefits and likely effectiveness of these reactions, and where impacts are likely to exceed the capacity of pastoralists to cope with the changes.
Research and promote greater use of strategic spelling and other improvements in grazing land management that reduce exposure to risks of climate variability and uncertain climate change.
Develop tools to determine regional safe stocking rates and pasture utilization levels linked to seasonal and projected climate conditions.
Assess animal management options such as modifying the timing of mating based on seasonal conditions.
Improve breeding and management of animal heat stress, particularly where livestock are handled more intensively.
Intensive Livestock
Analyse and develop policies that promote effective adaptation while reducing maladaptation and conflicting policy objectives. This would require comprehensive systems analysis of policy and management adaptation options.
Develop guidelines or building codes for energy and water efficient production sheds, particularly focussing on passive cooling or heating. Link these to revised capability to assess heat stress on livestock.
Understand the risks to feed supplies due to climate variability or reduction through competition from other users of feedstock.

Assess the vulnerability of irrigated dairy to reduced water supply.
Water Resources
Develop approaches to managing water resources that take into account climate change projections as well as seasonal to decadal drivers of climate variation.
Evaluate the costs and benefits of increasing on-farm and systems efficiencies via better use of technology, co-ordination of delivery mechanisms, evaporation control, retrofitting leaky systems, the provision of probabilistic seasonal forecasts, improved scheduling and better understanding of what is needed to implement such measures in a range of different circumstances.
Incorporate climate change considerations more effectively into integrated catchment management, addressing the relationships between water quality, surface and groundwater extraction, waterway management and land-use,. Institutional arrangements may need reviewing to encourage such integration.
Evaluate the implications of moving to full cost pricing and water trading so as to maximise the potential for adaptation and minimise perverse incentives.
Evaluate whether there are clear thresholds in irrigated agriculture (e.g. loss of flows from the MDB leading to the death of tree crops; in-stream salinity becoming too high for irrigation) and the implications of these for water resource management under climate change
Develop a framework for water resource management that takes account of on-going conditions, where business as usual, watching brief, near critical and emergency management are all codified stages that contain strategic considerations relevant to planning horizons under climate change.
Fisheries & Aquaculture
Undertake research on how fisheries and aquaculture management and policy can facilitate flexibility by operators seeking to adapt to climate change – are current management approaches suited to a changing climate?
Collect and analyse data on the impacts of climate variability and trends on marine biology to give insight into the impacts of climate change on fisheries and aquaculture and develop methods for assessing the vulnerability of fished and aquaculture species to environmental variables under climate change, including means, extremes, and cumulative impacts.
Develop robust genetic strains for aquaculture species that perform well in future environments, and examine industry locations and opportunities under future climate scenarios.
Develop predictive models for the occurrence of extreme events, and the thresholds for the biology (particularly for aquaculture). Deliver these warnings at a time in the production cycle that is useful to operators and build the capacity of these operators to integrate this information into their management plans.
Investigate regional case studies for the impacts of climate change on the biological, social and economic relationships in fisheries and aquaculture.

Region-specific considerations

The tabulated regional indications of climate change impacts are highly uncertain. Underpinning regional projections of climate change are themselves highly uncertain and span a wide range of variation (CSIRO 2007). Subsequent interpretations of impacts introduce added uncertainty about how biological systems will respond and are based on informed synthesis of current knowledge (rather than rigorous analysis). The following comments should therefore be used as an indication of the likely range of impacts for which primary industries will have to prepare, and NOT as reliable predictions of exactly where specific impacts will occur.

Table 1.3: Summary of regional variation in climate change issues for terrestrial primary industries. Australia has been divided into ten agro-climate zones (groupings of IBRA bioregions) following the regionalization of Hobbs & McIntyre (2005).



Industries	**Regional climate change impacts and issues**
- Cold wet	
Cropping	Very little cereal cropping practiced. Increasing temperatures may increase crop growths and expand the growing season.
Forestry	Much of this region is included in National Parks, so native tree species may be at risk from climate change, but few if any commercial forest areas would be affected.
Intensive livestock	Dairy likely to benefit from warming and drying. Possibly reduced energy demand for heating of productions sheds.
Water resources	Median greenhouse runoff projection slight decrease. Declining snowpack, making streamflow less reliable. Tasmania mainly self extracting; Kosciusko Plateau important source area for irrigation source water in MDB. Catchment risk score very low to low in Tasmania, moderate to high on the mainland.
- Dry	
Cropping	Cropping limited, restricted area of irrigation which may be challenged due to increasing demand but decreasing supply of water.
Forestry	Most of this region is too arid for commercial forestry though there may be some potential

Industries	Regional climate change impacts and issues
	for oil mallee and carbon sequestration plantings in the higher-rainfall edges of the region. Care should be taken in establishing and managing these plantations, as being in already relatively low rainfall areas they would be potentially vulnerable to any further rainfall reductions.
Grazing	This vast arid area is likely to experience the greatest warming and drying trends within the rangelands. This will further stress many enterprises that are already only marginally viable and where few opportunities for adaptation exist.
Water resources	Median greenhouse runoff projection positive in central south, slight decrease on fringes of region, especially in the east. Most of the irrigation in these areas is self extracting and opportunistic likely to more constrained. Catchment risk score very low (western half) and low to moderate (eastern half).
- Mediterranean	
Cropping	Potentially large reductions in rainfall will reduce yields markedly leading to flow on effects to regional communities and businesses. In such an eventuality, cropping will become more challenging at the current dry margins but may expand into areas currently generally too wet for regular cropping. There may be reductions in the risk of dryland salinisation. A range of adaptations, particularly aimed at improving crop water management.
Rice	Water supplies are projected to become more limited while individual crop demand is likely to increase. The likelihood of cold damage during flowering may decline, whereas risks of crop heat-damage may increase. There is some scope to adapt rice production in current ponded culture, however aerobic and alternate-wet-and-dry rice represent future adaptation options. A wide range of potential farming system changes need to be considered, including greater utilisation/understanding of seasonal climate forecasts.
Viticulture	Phenological shifts to winegrape vines may result in ripening in a warmer part of the season. Quality will be affected. Grapevine variety suitability will change and planting of ‘longer season’ varieties to fit the warmer climate will reduce any negative impact. Water may become a limiting factor for grape production in these regions.
Horticulture	Timing of crop cycles for annual horticulture crops may be hastened requiring crop scheduling and marketing responses. Reduction in chilling over winter may affect suitability for growing of some perennial fruit crops. Increasing frequency of extreme temperature events resulting in undesirable physiological responses must be managed. Water availability and security of supply is essential, especially for perennial horticulture.
Forestry	There are major areas of commercial plantings, particularly in Western Australia and South Australia. Bioclimatic analysis should be used to identify particularly vulnerable *E. globulus* (blue gum), *P. radiata* (radiata pine), *P. pinaster* (maritime pine) and oil mallee plantings, so these can be monitored to provide early warning of any problems. Many eucalypts in native forests in the southwest have narrow climatic ranges and may be particularly vulnerable to climate change.
Intensive livestock	Irrigated dairy likely to be impacted by reduced water allocation, and increased temperatures. Landscape rehydration through wetland creation is a priority. Heat stress issues for stock. Increased energy demand for cooling production sheds; increased demand for new energy efficient designs or retrofitting of exiting sheds.
Water resources	Median greenhouse runoff projection moderate to large decrease for the south-west component and substantially negative for south-east component. In the south-east, most water sourced from upstream in the MDB. Increased demand and reduced supply a substantial issue in both regions. Catchment risk score moderate to very high (west) and low to very high (east).
- Subtropical moist	

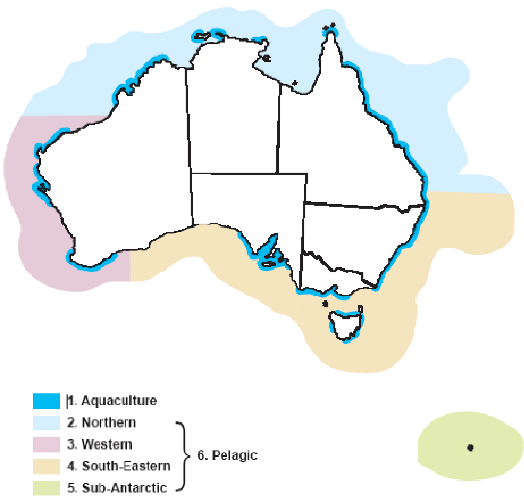
Industries	Regional climate change impacts and issues
Cropping	Cropping limited in area, restricted area of irrigation which may be increasingly challenged due to increasing demand from climate and other users but decreasing supply of water.
Sugarcane (Southern region)	Present limited supply of irrigation water is likely to be exacerbated by the projected decrease in rainfall. Adaptation must focus on improved efficiency of water use. Projected warming will increase the duration of the growing season. Planting earlier in the season needs to be considered in a value-chain contest. Present competition for land-use from other crops may increase, particularly from short-duration annual crops. Diversification options also need to be considered in terms of short, medium and long-term climate change projections.
Horticulture	Frost reduction in these regions may see expansion of horticultural production suited to this climate. Crop phenology will be affected requiring intake scheduling and marketing responses for vegetable cropping.
Forestry	There are significant areas of hardwoods particularly *E. pilularis* and *E. grandis*. Preliminary analyses suggest neither species is likely to be at high risk in this region, but care should be taken to look for any developing problems, such as reduced productivity or new pests and diseases.
Intensive livestock	Irrigated dairy likely to be impacted by reduced water allocation, and increased temperatures. Heat stress issues for stock. Increased energy demand for cooling production sheds; increased demand for new energy efficient designs or retrofitting of exiting sheds.
Water resources	Median greenhouse runoff projection slight decrease. Local concentrations of irrigation (mainly self extraction) will be affected. Drier conditions with increased flood risk from east coast lows likely. Most storages not as substantial as those inland. Catchment risk score moderate to very high.
- Subtropical sub-humid	
Cropping	Potentially significant reductions in yield and quality of winter crops such as wheat due to likely reductions in rainfall and existing exposure to high temperatures in the northern part of this region. Potential reductions in frost may increase crop options. Summer rainfall seems equally likely to increase as to decrease and this also may provide some options to alter the balance of cropping. Adaptations include increased opportunistic cropping, increased attention to managing stored soil moisture and the use of seasonal climate forecasts.
Cotton	Less irrigation water, higher temperatures and greater evaporative demand by crops will impact yield and fibre quality. Improved water use efficiency (irrigation practice and variety choice) and tolerance to heat stress (variety choice) and modification of crop management (planting date, row configurations, irrigation scheduling) will need to be re-considered to help offset these issues.
Forestry	Plantation forestry is not a major activity in the Brigalow belt. The dominant species *Acacia harpophylla* (Brigalow) is widely distributed and is unlikely to be at high risk from climate change.
Grazing	The negative affects of declines in rainfall and increasing incidence of drought on the productivity of these savannas may initially be offset from by the benefits of higher CO_2 and a prolonged growing season from warming. More intense rainfall may increase the risks of soil erosion, rising CO_2 may favour trees at the expense of pasture production, and pasture quality may decline.
Intensive livestock	Feedlots are likely to be impacted by increased temperatures and reduced water availability. Increased energy demand for cooling production sheds; increased demand for new energy efficient designs or retrofitting of exiting sheds.

Industries	Regional climate change impacts and issues
Water resources	Median greenhouse runoff projection large decrease. Warmer conditions will increase water stress. Self-extracted water sources less well buffered than distributive systems. Catchment risk score high to very high.
- Temperate cool-season wet	
Cropping	Potentially significant reductions in yield of winter crops such as wheat due to likely reductions in rainfall. Reductions in irrigations water may push existing irrigated systems into a more opportunistic mode where there is partial irrigation or irrigation only once every several years on average. Adaptations include a range of changes in crops and crop management, increased opportunistic cropping, increased attention to managing stored soil moisture and the use of seasonal climate forecasts, increased water use efficiency.
Viticulture	Some areas, previously too cool for viticulture may become suitable. Some varieties that would not ripen in the present climate may be successfully planted in the future warmer climate. Phenological shifts to existing winegrape vines may result in ripening in a warmer part of the season. Quality will be affected. Grapevine variety suitability will change and planting of 'longer season' varieties (than presently planted) to fit the warmer climate will reduce any negative impact. Water may become a limiting factor for grape production in these regions. Disease incidence may reduce with lower rainfall in spring.
Horticulture	Extreme temperature impacts resulting in damage and/or undesirable crop physiological responses will need to be managed. Disease/pest impacts may be reduced with lower projected rainfall. Phenological and cropping cycles may be reduced. Some presently marginally cool regions may become more suitable for horticultural production. Security of supply of water is required especially for perennial horticulture.
Forestry	This is one of the most important plantation areas, including all or part of the Green Triangle (southern SA and southwest Vic), Tasmania, Central Victoria, Murray Valley, Central Gippsland, East Gippsland, Southern Tablelands, Central Tablelands and Northern Tablelands National Plantation Inventory regions. *P. radiata* and *E. globulus* are the major species. Likely impacts of climate change on these plantations are being analysed by CSIRO Forestry as part of a project for Forest and Wood Products Australia.
Intensive livestock	Dairy likely to benefit from warming, particularly in Tasmania. Some heat stress issues for stock. Possible increased energy demand for cooling or warming production sheds; increased demand for new energy efficient designs or retrofitting of exiting sheds.
Water resources	Median greenhouse runoff projections slight decrease (coastal) to moderate decrease (inland). Internal catchment water sources in the south and east and important source area supplying downstream MDB in the north. Disappearing snow pack in higher areas. Local irrigation will not be as affected as warmer areas. Flood risk in the east probably increased. Catchment risk score moderate to very high.
- Temperate subhumid	
Cropping	Potentially significant reductions in yield of winter crops such as wheat due to likely reductions in rainfall. Reductions in irrigations water may push existing irrigated systems into a more opportunistic mode where there is partial irrigation or irrigation only once every several years on average. Adaptations include a range of changes in crops and crop management, increased opportunistic cropping, increased attention to managing stored soil moisture and the use of seasonal climate forecasts, increased water use efficiency.
Cotton	Warmer conditions may allow for improved growing conditions (longer seasons) leading to possible industry expansion, if irrigation water is available.
Rice	Water supplies are projected to become more limited while individual crop demand is likely to increase. The likelihood of cold damage during flowering may decline, whereas

Industries	Regional climate change impacts and issues
	the risk of crop heat-damage may increase. There is some scope to adapt rice production in current ponded culture, however aerobic and alternate-wet-and-dry rice represent future adaptation options. A wide range of potential farming system changes need to be considered, including greater utilisation/understanding of seasonal climate forecasts.
Forestry	This region includes part of the Western Slopes of New South Wales. Forestry is not a major activity in the region at present, but there may be future oil mallee plantings for carbon sequestration. Care should be taken in establishing and managing these plantations, as being in already relatively low rainfall areas they would be potentially vulnerable to any further rainfall reductions.
Intensive livestock	Irrigated dairy likely to be impacted by reduced water allocation, and increased temperatures. Heat stress issues for stock. Increased energy demand for cooling production sheds; increased demand for new energy efficient designs or retrofitting of exiting sheds.
Water resources	Median greenhouse runoff projection moderate decrease. Region mostly sources water from further east subject, to moderate decrease also. Increase in water stress and storages not as large as on Murray system, so less carry-over resource. Catchment risk score high to very high.
- Tropical warm-season moist	
Cropping	Sugarcane the dominant crop. As discussed in the chapter on sugarcane, in the north of this region, prospects of lower rainfall may increase yields through increased sunshine but in the south, reductions in rainfall will reduce yields or increase demands for increasingly scarce irrigation water. Some increase in risks of soil erosion and pests and diseases. Adaptations in planting regimes and changing harvest chain.
Cotton	Development of a sustainable cotton cropping system for the Burdekin Irrigation Area
Sugarcane (Northern, Herbert & Burdekin and Central regions)	Crop damage from wind and cyclones may increase. Nutrient and sediment runoff into the Great Barrier Reef lagoon may increase. Northern region: Increased waterlogging may limit paddock access, particularly during the growing season. Reduced spring rain would negatively impact crop establishment. Herbert & Burdekin region: The security of water supply from the Burdekin Dam may be threatened. Rising water table and salinity issues, exacerbated by rising sea levels, will require improvements in irrigation. Declines in winter and spring rain may increasing trafficability, improving harvesting efficiency. Central region: Limited water supplies may be further strained by projected drying. Warming will extend growing seasons and improve crop growth in the frost-prone western districts. Poor drainage and tidal intrusion in the lower floodplains are likely to be exacerbated by projected sea level rise.
Horticulture	Expansion of industry may occur with decreased frost risk. Heat stress/flooding/erosion/ and cyclones can all have devastating impacts and risk assessments will need to be undertaken with regard to these. Cropping cycles will change with increasing temperatures and intake scheduling and marketing responses will need to be adjusted.
Forestry	South East Queensland is the major forestry centre in this region, with pine species accounting for about 83% of the plantation area. The same species, *P. elliottii* (slash pine) *P. caribaea* (caribbean pine) and their hybrid, as well as the native *Araucaria cunninghamii* (hoop pine) are grown further north, so selected sites should be monitored to provide some early warning of any problems associated with climate change.
Grazing	Productivity of these savannas may be negatively affected by some decline in rainfall and increasing incidence of drought. More intense rainfall may increase the risks of soil erosion, rising CO_2 may favour trees at the expense of pasture production, and pasture quality may decline.

Industries	Regional climate change impacts and issues
Intensive livestock	Irrigated dairy likely to be impacted by reduced water allocation, and increased temperatures. Heat stress issues for stock. Cloud cover during wet season will continue to be an issue for pasture growth in the north. Increased energy demand for cooling production sheds; increased demand for new energy efficient designs or retrofitting of exiting sheds.
Water resources	Median greenhouse runoff projection slight to moderate decrease. Local concentrations of irrigated tropical agriculture at risk of drought. Cyclone and storm damage risk may increase. Catchment risk scores moderate to very high.
- Tropical warm-season wet	
Cropping	Limited dryland cropping with summer crops such as sorghum and also some irrigated crops. All crops are likely to be increasingly negatively affected by high temperatures but if increases in rainfall occur (approx 30% probability) this may alleviate restricted growing seasons for the dryland crops in particular.
Cotton	Establishment of sizeable cotton industry within the Ord Irrigation Area
Horticulture	Expansion of industry may occur with decreased frost risk. Heat stress/flooding/erosion/ and cyclones can all have devastating impacts and risk assessments will need to be undertaken with regard to these. Cropping cycles will change with increasing temperatures and intake scheduling and marketing responses will need to be adjusted.
Forestry	The area of plantations in the Northern Territory is relatively small, but expanding rapidly. The total area in 2005 was about 16,000 ha, of which 85% were *Acacia mangium.* Similar areas of *Khaya senegalensis* (African mahogany) are likely to be planted in coming years.
Grazing	Northern savannas are likely to be the rangelands where productivity is least affected by climate change. But more intense rainfall may increase the risks of soil erosion, rising CO_2 may favour trees at the expense of pasture production, and pasture quality may decline.
Intensive livestock	Not applicable for dairy. Increased energy demand for cooling production sheds; increased demand for new energy efficient designs or retrofitting of exiting sheds.
Water resources	Median greenhouse runoff projection slight increase on Cape York to slight decrease further west. Substantial wet season but only one substantial water storage: Lake Argyle. Catchment risk scores very low to low in the west and low to moderate on Cape York.
- Tropical wet	
Cropping	Sugarcane the dominant crop. As discussed in the chapter on sugarcane, prospects of lower rainfall may increase yields through increased sunshine. Some increase in risks of soil erosion and pests and diseases. Adaptations in planting regimes and changing harvest chain.
Forestry	The plantation area of the Ingham-Cairns region of North Queensland is not large, but it may provide some useful early warning of possible climate change problems with growing pine species important in South East Queensland under warming conditions. Conserving highly species diverse tropical rainforests in their current condition may be difficult under climate change. However, the diversity of species may provide some capacity to adapt to climate change.
Intensive livestock	Not applicable for dairy. Increased energy demand for cooling production sheds; increased demand for new energy efficient designs or retrofitting of exiting sheds.
Water resources	Median greenhouse runoff projection slight increase. No notable irrigation. Catchment risk scores low to moderate.

Table 1.4: Summary of regional variation in climate change issues for Australian fisheries and aquaculture. Pelagic fish occur in most zones and are treated separately. A more detailed map is provided in Figure 12.1.



Region	Regional climate change impacts and issues
- Northern	Changes in patterns of rainfall and freshwater flows may impact important nursery areas, such as estuaries and mangroves, indirectly impacting fisheries catch. Biological responses to increased temperature include enhanced recruitment and growth of some species such as prawns. Sea level rise and extreme events (storms and cyclones) intensity will increase risks to infrastructure for aquaculture, such as prawn ponds, and nursery areas for wild fisheries.
- Western	Potential changes in the Leeuwin Current are not well described in climate models due to scale of models, but some weakening has been predicted. The overall pattern in temperature change is uncertain. A number of commercially fished species are closely linked to Leeuwin Current dynamics, so responses are expected to any physical change. Increase in extreme events may impact aquaculture operations (e.g. oyster farming) and changes in sea level need to be considered by coastal aquaculture operations.
- South-eastern	A strengthening of the East Australia Current will enhance increases in water temperatures in south east Australia (projected to be greatest anywhere in southern hemisphere). Southward shifts in species' ranges have already been recorded in conjunction with change over the past 30 year. Possible increases in wind-driven upwelling in the Great Australian Bight, resulting in increased productivity at the base of the food chain. Wind is related to recruitment cycles of some wild fished species, however, changes due to climate not well resolved. Warming waters have implications for aquaculture operations, such as salmon farming.
- sub-Antarctic	Sea ice expected to become more seasonal and decline in northern extent. Increased temperatures will increase growth rates of some species (up to a point). Increased acidification is expected to reduce productivity at the base of the food chain.
- Pelagic	In offshore parts of all regions changes in distribution with changing temperature are expected, particularly in south-east Australia. Greater availability of tropical species may occur, and reduced availability of temperate species that move southwards.

Notes

- This review was prepared by a small, cross-disciplinary team of researchers with valuable input from relatively few industry participants. It expands, updates and builds on a previous report prepared for the Australian Greenhouse Office in 2003 (Howden *et al.* 2003). Due to the limited participation and the paucity of existing analyses of benefits and costs of implementation of adaptation strategies, this study should be seen as a starting point from which to engage with primary industries – not a final analysis.
- As part of a parallel process to this review, Land and Water Australia have commissioned a set of consultations with key representatives of Australia's primary industries. Both sources of feedback will be used in prioritising and planning future research and management needs for preparing Australian agriculture for climate change.
- Literature cited in the Executive Summary is listed in the Reference section of the Introduction.

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1: INTRODUCTION

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Key Messages:

- The climate is changing and further change seems inevitable even if greenhouse gas emissions were to be reduced. For primary industries to continue to thrive in the future we need to anticipate these changes, be prepared for uncertainty, and develop adaptation strategies now.
- Some broad generalizations can be made about how plant growth, which underpins all the primary industries addressed in this report, will be affected by climate change. Warmer temperatures may benefit perennial plants in cool climates, but annuals and plants growing in hot climates may be negatively affected. Plant productivity would be expected to increase or decrease in accord with any changes in rainfall, while the direct effects of CO_2 in stimulating plant growth and increasing water use efficiency could help by partly offsetting increases in evaporation or decreases in rainfall.
- While there are some general principles about how impacts of climate change will vary geographically, regional climate change projections are currently more useful for describing the wide range of uncertainty and for probabilistic risk assessment than serving as reliable predictors for planning and decision making.
- Adaptation will need to take a flexible, risk-based approach that incorporates future uncertainty and provides strategies that will be able to cope with a range of possible local climate changes. Initial efforts in preparing adaptation strategies should focus on equipping primary producers with alternative adaptation options suitable for the range of uncertain future climate changes and the capacity to evaluate and implement these as needed, rather than focussing too strongly yet on exactly where and when these impacts and adaptations will occur.
- In the short-term, a common adaptation option will be to enhance and promote existing management strategies for dealing with climate variability. This will automatically track early stages of climate change until longer-term trends become more clear.
- Marginal production areas are amongst the most vulnerable and will likely be amongst the first areas in which the impacts of climate change will exceed adaptive capacity. It will be important to identify areas where climate change risks and opportunities require strong policy intervention (beyond simply supporting adaptation within existing land uses) such as transformation to new land use activities.

Our changing climate

There is now widespread acknowledgement that climate change has already occurred, that future change is almost inevitable, and that we will have to adapt to these changes (IPCC 2007c; IPCC 2007a). Furthermore, future impacts and adaptation requirements will be dependent on the urgency and effectiveness with which mitigation measures are implemented (Howden *et al.* 2007). The recent IPCC Fourth Assessment report concludes that Australia has significant vulnerability to the changes in temperature and rainfall projected over the next decades to 100 years (Hennessy *et al.* 2007). Agriculture and natural resources were two of the key sectors identified as likely to be affected strongly. Climate change will add to the existing, substantial pressures on Australia's primary industries. To be prepared for these changes, we need to start developing and implementing adaptation strategies now. As a first step, identifying common adaptation issues among Australia's various primary industries will provide a means for prioritizing actions and investments. This review is aimed at assisting such efforts.

It is very likely that human activities are affecting the global climate (IPCC 2007c). Global mean temperatures have risen approximately 0.76°C since the mid 1800s and changes in rainfall patterns, sea levels, and rates of glacial retreat have also been detected which are consistent with expectations of 'greenhouse' climate change. The 1990s were the warmest decade ever recorded instrumentally, and the last 100 years were the warmest of the millennium. The most recent report of the Intergovernmental Panel on Climate Change (2007b) concluded that there is now strong evidence for a human influence on global climate and that these trends will continue for the foreseeable future due to continued emissions of fossil fuels and other greenhouse gases. The most up to date predictions are for an increase in global average temperatures of 1.1-6.4°C by the end of the present century. To place these changes in perspective, a 1°C rise in average temperature will make Melbourne's climate like that currently experienced by Wagga, a 4°C rise like that of Moree and a 6°C rise like that just north of Roma in Queensland. Intuitively, it is hard to conceive that such changes will not have implications for Australia's agricultural industries.

The importance of developing effective strategies for adapting to climate change has been recognised by the governments of the Commonwealth, States and Territories. For example, former Environment Minister Turnball stated that, "Climate change is a fact, not a theory. It is happening now, and it presents one of the greatest environmental and economic challenges the world has ever faced" (Australian Greenhouse Office 2007). Initiatives such as the recently-commissioned Garnaut Climate Change Review (http://www.garnautreview.org.au) are seeking to more fully understand the implications of climate change and the actions that could be taken to address this challenge. It is now recognised that in order to assess the costs (and benefits) of climate change we need to include the costs (benefits) of mitigation and costs (benefits) of impacts and the costs (benefits) of adaptation. Several of these interact with each other. For example, we would expect that the size of the adaptation task will be lower if there is effective, but perhaps costly mitigation and higher if mitigation is foregone (Howden *et al.* 2007). Similarly, the benefits of effective adaptation are likely to be greater if the climate change itself is large. Achievement of this complex task of effectively informing public policy development will be challenging in its own right – and this study is a step towards that goal.

In this study we focus on all the major primary industries in Australia: grains (Chapter 2), cotton (Chapter 3), rice (Chapter 4), sugarcane (Chapter 5), viticulture (Chapter 6), horticulture (Chapter 7), forestry (Chapter 8), grazing (Chapter 9), intensive livestock (Chapter 10), water resources (Chapter 11) and fisheries and aquaculture (Chapter 12). The total gross value of production of these industries is about $40 billion p.a. and it has been increasing at about 3.3% per year over the past decade (ABARE 2007). In the year 2006-7, exports from these industries were about $31.4 billion - about

15% of total exports. Hence, agriculture makes a substantial contribution to the national balance of trade. Throughout this chapter terms such as ‘agriculture’, ‘enterprise’, ‘land use’ and ‘primary producer’ are used to refer more broadly to the full range of industries that Australia’s renewable natural resources support.

Past experience demonstrates that all these sectors have sensitivity to climate variations ranging from minor to substantial. Therefore, we anticipate that climate changes are likely to have some impact and that adaptations will often be needed to both offset negative impacts and take advantage of positive impacts. We have also included cross-cutting issues of water resources and pests/diseases as previous work has demonstrated that these are highly sensitive to potential climate changes and they have significant implications for components of the agricultural sector. The material on pests and diseases is integrated into each sector as this will be how the impacts are largely expressed whilst water resources are dealt with in a separate chapter.

There are several impacts of climate and atmospheric composition which are common across these sectors as they impact on plant production – the primary driver for agriculture. The next section of the report deals with these common responses.

Primary impacts of atmospheric and climatic change

The high diversity of Australian agricultural and marine systems necessitates that individual approaches to adaptation to climate change will be similarly diverse. As there are a plethora of small and large, unquantifiable and substantially unpredictable climatic change impacts, that develop intermittently through time and that interact with other environmental, economic, social and adaptive changes it is logical to first consider the most direct and most immediate effects and then build outwards with less certain and more distant potential impacts later. Hence, we first deal with the impacts of rising atmospheric CO_2, then address rising temperatures and then changes in rainfall and marine impacts. We then consider the timeframes for change, regional variation in climate projections and lastly vulnerability and adaptation.

Direct effects of rising atmospheric CO_2

The steadily increasing concentration of CO_2 in the atmosphere directly affects resource use efficiency, productivity, and product quality of plants and vegetation.

Elevated atmospheric CO_2 concentration increases the efficiency of use of light and water (Gifford 1979; Morison and Gifford 1984), nitrogen (Drake *et al.* 1997) and possibly efficiency or effectiveness of uptake of other minerals like soil phosphorus (Campbell and Sage 2002). In Australia where water, nitrogen and phosphorus are major limiting factors in production, this is an important first order feature of the response of primary industries to global atmospheric change. The responses to CO_2 represents a form of automatic self-adaptation of the agricultural system to atmospheric change upon which any less certain impacts of local climatic change are superimposed. As such it is appropriate to understand it and to consider how this self-adaptation might interact with the changes in weather and might be maximised. Since atmospheric CO_2 concentration has been recorded to be increasing for 150 years this internal adaptive response will have been going on progressively over that time. And indeed the once-dubbed "missing carbon sink" in the global carbon budget is now regarded as at least substantially attributable to that "CO_2 fertilising effect" on vegetation (IPCC 2000).

The increase in light use efficiency in C_3-species, like wheat, barley, rice, cotton, oats, oil seeds, trees, and cool-season pasture species, derives substantially from the suppression of the process of photorespiration by elevated CO_2. The C_4 species (maize, sorghum, sugarcane and tropical grasses) lack photorespiration and the effect of CO_2 on increasing light use efficiency is correspondingly much lower in these species.

The increase in water use efficiency is attributable to a stronger CO_2 concentration gradient from the air to the inside of the leaf, which increases the rate at which CO_2 enters into the leaf through stomata relative to the rate at which water vapour diffuses out of the leaf. Depending on how plants adjust their stomatal closure under elevated CO_2, increases in water use efficiency can be expressed as an increase in photosynthesis while transpiration rates stay the same, reduced transpiration while photosynthesis remains the same, or an intermediate combination of increased photosynthesis and reduced transpiration. In the field, this may be expressed as an increase in growth rate while soil water depletion remains unaltered or reduced soil water depletion with little growth effect (or an intermediate combination). This increase in plant dry matter production per unit of water used by plants occurs in both C_3 and C_4 species (Morison and Gifford 1984). The increased efficiency with which plants use water needs to be exploited in developing adaptation strategies and could be use to partly offset the effects of reduced rainfall or increased evaporative demand.

The increase in nitrogen use efficiency (here referring to the capacity to grow more dry matter with the same amount of nitrogen) can occur in C_3 species through down-regulation of photosynthesis where plants compensate tor the increased efficiency of "rubisco" (a key photosynthetic enzyme that contains a large fraction of the leaf's nitrogen) by producing less of this enzyme. Thus the N-content of the leaf decreases. Another reason for reduced N-concentration in plant tissues is because of passive 'dilution' whereby elevated CO_2 stimulates carbon fixation, and storage of carbohydrates but the increased input of carbon to plant tissues from the atmosphere is not matched by corresponding increases in uptake of N by plant roots. These changes in protein and storage carbohydrates have implications for plant product quality such as herbage forage quality and possibly grain quality. Adaptive management measures may be needed to compensate for these impacts where they are problematic, but in some circumstances these impacts can be beneficial (e.g. in livestock where growth is energy limited not N-limited).

In legume species that are fixing N biologically via symbiotic N-fixation in the roots, elevated CO_2 concentration has frequently been shown to increase the rate of N-fixation per plant or per unit ground area by increasing the size of the root system and mass of nodules. Additionally, the growth response of legumes to elevated CO_2 concentration is generally greater than that of grasses. Thus in mixed farming systems using legume-based leys the need for artificial fertiliser, to maintain grain protein levels for example, may be expected to decline (all else being equal).

Annual warming

The primary climatic effect of increasing concentrations of greenhouse gases is an increase in the average temperature of the lower atmosphere. The rate of plant development is approximately linearly dependent on cumulative air temperature ("heat sum") above a base temperature at which development rate is essentially zero. In addition, plant growth rate shows a flat bell shaped response to temperature with each species having its own optimum temperature characteristics. The optimum is, however, subject to acclimation such that plants within a species growing in high temperatures have a higher optimum than those growing in low temperatures. Generally speaking, most agricultural crops grow in areas where average temperatures are below their acclimated optimum. Thus as temperatures rise (and all else being equal) we might expect both dry weight growth rates and rates of progression through developmental phases to increase with the effect on rate of development being the stronger of the two. However, plant responses to possible changes in frequency of occasional high temperature or frost stress make generalisation very problematic. For annual crops, warmer conditions tend to reduce yields owing to any faster growth rate not being sufficient to compensate for the earlier attainment of maturity.

For perennials such as trees and pasture species in regions where cool winters slow growth, it might be anticipated that warming would increase winter growth and extend the more rapid growth period. However, for the perennial subterranean clover it was found that 3.5°C continuous warming of the atmosphere in a field experiment did not increase winter growth and for the whole year decreased herbage growth by almost 30%, offsetting a positive response to concurrent elevated CO_2 concentration (Lilley *et al.* 2001). The temperature responses of productivity are clearly complex, involving interdependent effects on photosynthesis, respiration, transpiration, nutrition, and plant development.

On top of the increase in air temperature, the reduced stomatal aperture in the higher CO_2 concentration causes less evaporative cooling and hence a larger leaf to air temperature differential. Thus, plant temperatures by day will tend to increase faster than air temperatures. Past analyses had indicated that night-time temperatures may have increased faster than daytime air temperature, but the most recent analysis has not found any differences in rates of warming over the period 1979 – 2004 (IPCC 2007c). The effects of differential changes in day versus night temperature increases are little studied on agricultural crops. Protected horticultural crops, for which varying night temperature is a management option however, have been much investigated for night temperature effects. Numerous developmental and product quality effects such as on flowering, plant height, seed set and fruit attributes have been recorded. At least some of these responses are reported also in the few studies on field crop species. In a study of night temperature effects on sorghum and sunflower, Manunta and Kirkham (1996) concluded that warmer night temperatures increase plant respiration more in C_4 than in C_3 species. In rice increased night temperature for a constant 29°C day temperature did not affect yield while increasing night temperature for a constant 33°C day temperature caused a higher level of sterility (Ziska and Manalo 1996). Thus adaptive management in relation to increasing night temperatures may have some different species (or genotype) by environment interactions to take account of. The database is far too small for specific adaptive recommendations to be made on such matters at this stage.

In addition to the above effects, minimum temperature is inversely related to vapour pressure deficit (VPD: the ‘dryness’ of the air) which is in turn linearly related to evaporation rates. High vapour pressure deficits also result in lower water use efficiencies. Thus if VPD increases there is a negative double impact (high water demand and low water use efficiency). However, as discussed in the ‘Moisture Conservation’ section of the cropping chapter, if minimum temperatures continue to increase at a faster rate than maximum temperatures, then VPD and evaporation rates will not necessarily increase – unlike the scenarios in many projections. Unfortunately, GCMs are not yet informative of the balance between minimum and maximum temperatures in the future (le Treut 1999).

Interactions between elevated CO_2 concentration and temperature are complex. Although there seemed to be solid theoretical reasons why the magnitude of the CO_2 response of growth of C_3 species would increase with growth temperature (Gifford 1992) synthesis of experimental evidence from the literature indicated no trend of increased CO_2 sensitivity with increasing temperature (Morison and Lawlor 1999). Hence, we cannot assume that the responsiveness of plant growth to CO_2 will become greater with global warming.

Increased intensity of the hydrologic cycle

Implicit in the theory of global warming is a positive feedback of increasing greenhouse gas concentrations via atmospheric water vapour involving intensification of the hydrologic cycle. This means higher evaporation rates, higher absolute atmospheric humidity and higher rainfall. However, the places where evaporation may increase is not necessarily the same as those where rainfall may increase. While greenhouse science popularisation has made much of the idea that global warming will bring increased frequency and intensity of droughts in Australia, it is not necessarily true. Recent climate model projections for Australia (CSIRO 2007) depict a complex spatial and seasonal pattern of increases and decreases of rainfall with wide margins of uncertainty that range into both increases and decreases as possible for all areas of the country in all seasons (see "Regional Climate Change Projections" below). For example in the area that is often stated to have the most consistent projection of drying (the SW of WA), a 5% increase in rainfall by 2070 is presented as just as likely as a 20% decrease. Obviously, such predictions offer moderate information for adaptive planning at the enterprise level except to be alert for the unexpected. In terms of agricultural productivity yield is generally proportional to rainfall, but that the way that rain falls (i.e., seasonality and intensity) can have significant impacts on productivity and natural resources (e.g. through salinity and erosion). The increasing atmospheric CO_2 concentration will help alleviate the impact of reduced rainfall where this occurs. However, within this apparent simple picture, lies enormous complexity and diversity of response across the agricultural industries.

Marine impacts

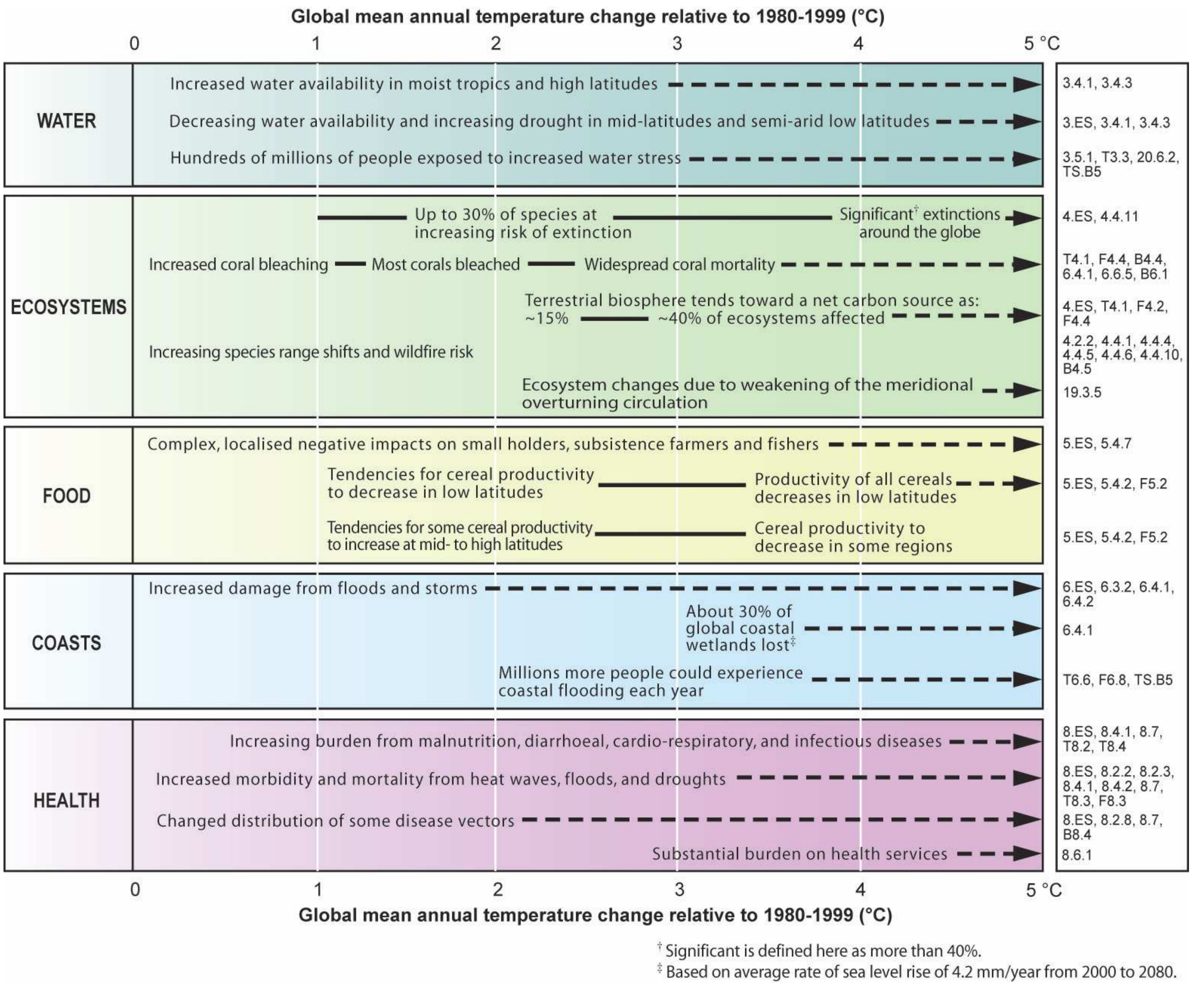
The dominant climate change influences on marine environments will be warming of the oceans, changes in circulation patterns and changes in ocean chemistry. Increasing temperatures in oceans will be expected to threaten coral reefs with more frequent bleaching episodes, cause fish species to migrate towards the poles, and threaten southern kelp forests (Hennessy *et al.* 2007). Oceans serve as a strong buffer for atmospheric CO_2 levels and have been estimated to have absorbed about of half of all anthropogenic CO_2 emissions to date. However, the ability of oceans to absorb CO_2 will decline as oceanic CO_2 concentrations rise (CSIRO 2007). Rising levels of CO_2 in oceans are increasing their acidity and reducing the availability of calcium carbonate, which is required by many creatures with calcium carbonate-based shells: evidence from the southern ocean suggests this decline has already begun. Increased stratification of oceans will reduce overturning and nutrient cycling and this could alter productivity, particularly in upwelling regions. Estuaries, which are important nurseries, are likely to be affected by rising sea levels and changes in flows of freshwater from rivers.

Timelines

The most immediate effects of rising atmospheric CO_2 on primary industries will be through the direct effects of CO_2 on plant growth. Anthropogenic emissions of CO_2 mix rapidly through the atmosphere across the globe (within years) and immediately affect plant growth. The benefits of elevated CO_2 to plants diminish with each additional increase in CO_2 concentrations, plateauing at CO_2 concentrations of about 600 to 700 ppm. Since current the atmospheric CO_2 level (about 384 ppm) already represents a substantial increase over pre-industrial levels (about 280 ppm), current plant growth is already expressing more than a third of the maximum possible benefit that rising CO_2 are likely to provide to plants, and about half of the benefit that would be provided from CO_2 levels projected for the end of the century. Secondary and tertiary effects of changes in plant growth on nutrient cycling, hydrological feedbacks and other trophic levels (herbivores, pests, diseases, soil microbes) will take longer to be fully expressed.

In contrast, the effects of rising atmospheric CO_2 on global warming and climate change lags several decades behind increases in CO_2 levels. The IPCC (IPCC 2007a) summarised the timing of key impacts of climate change as a function the magnitude of global warming required for these impacts to take effect (Figure. 1.1). Some of the impacts that are likely to be expressed during the earliest stages of global warming are changes in latitudinal distribution of rainfall and negative impacts on ecosystems. Small increases in temperature may negatively affect crops growing near the tropics while benefiting crops in cooler climates, but further warming will start to negatively affect even crops at higher latitudes.

Figure 1.1: Illustrative examples of key impacts of climate change as a function of increasing global average termperature change (IPCC 2007a). The left hand edge of text entries indicate the approximate onset of impacts. Solid lines link impacts and dotted arrows indicate impacts that continue with increasing temperature. (Notes in the column on the right indicate the sections of the IPCC report where the impacts are coverd.)



It should be noted that the beneficial effects of rising CO_2 tend to precede the negative impacts. The positive effects will tend to approach their maximum potential or even start declining again during the early stages of climate change over the next half a century, whereas the negative effects will become increasingly strongly expressed over the longer-term and with greater rates of CO_2 emission. Caution will therefore have to be emphasised in the early stages of climate change to ensure that this does not engender a false sense of security or renewed scepticism about the magnitude of challenges that lie ahead.

Regional climate change projections

There is growing confidence in global scale observations and predictions of climate change, but these changes will not be expressed uniformly across the planet. At present, it is difficult to precisely determine how spatial variation in impacts of climate change will translate into impacts at regional and land management scales. Nonetheless, there are some general principles about how climate change will differ between locations and current climate models give some indication of where impacts are likely to be most severe.

Some of the factors that will modify changes in climate at a given location include latitude, distance from the coast, local topography, and changes in circulation patterns, particularly for important weather-generating systems (CSIRO 2007; Christensen and Hewitson 2007). High latitudes are expected to experience more pronounced warming than the tropics, but this pattern is likely to be largely restricted to the northern hemisphere (with its larger ratio of land to sea) and latitude is not projected to have a strong effect on warming in the southern hemisphere. However, changes in the Hadley circulation, sea level pressure and rainfall are generally expected to be strongly related to latitude. The Hadley Circulation (hot moist air rising near the tropics and descending at about 30^{O} N and S) is projected to expand poleward and weaken, accompanied by an increase in sea level pressure at mid latitudes and a poleward shift in storm tracks. Rainfall is projected to increase in the tropics, particularly in the tropical Pacific, accompanied by increases in the intensity of monsoonal rains. In the subtropics, rainfall is projected to decline, but at higher latitudes, rainfall is projected to increase again. Increases in temperature are likely to be greater on land than at sea, and warming is likely to be most extreme in the interiors of continents. However, coastal areas will be exposed to risks of inundation and salt water intrusion from rising sea levels. Coastal regions may also be exposed to more frequent and severe storms and tropical cyclones. Local influences of circulation patterns, topographic features and weather systems are much more difficult to predict, particularly at local land management scales. Even subtle changes in wind patterns and storm tracks can redistribute rainfall between regions. As more of these factors are understood and incorporated into models, confidence in regional and local projections of climate change will continue to improve. But regional and local projections from climate models are likely to remain highly uncertain and more suitable for analysing risk than serving as reliable predictors for adaptive planning.

The recent Climate Change in Australia report provides a comprehensive overview of projected patterns of future change in Australia's climate (CSIRO 2007). We summarise some of the key findings here, but the original report and associated internet site should be consulted for further detail (http://www.climatechangeinaustralia.gov.au). Temperatures in Australia are projected to increase by 1 to 5^{o}C, depending on location and emissions scenarios (CSIRO 2007) (Figure 1.2). The greatest warming is expected in the interior of the continent, particularly towards the northwest of the country. However, at fine scales, mountainous terrain can strongly modify temperature changes projected in course-scale (250 km grid cells) climate models, with additional warming at higher elevations.

Associated with these temperature increases will be marked increase in the frequency of hot days and warm nights, but a less-marked decrease in the frequency of frosts (CSIRO 2007). Regional changes in rainfall are very sensitive to changes in circulation patterns, so future rainfall is difficult to predict and there is lower confidence in regional projections of rainfall than temperature. The range of uncertainty in rainfall projections (10^{th} – 90^{th} percentile) spans both drying and wetting trends at most locations in Australia across a broad range of emissions scenarios (CSIRO 2007). Median rainfall projections, which could perhaps be viewed as the 'best estimates, show a general pattern of drying across the continent that is strongest in the southwest. Drying trends are weaker in the east of the country, and the northern tropics are the least likely to experience declines in rainfall (Figure 1.3). Aside from changes in the amount of rainfall, there are also projected to be changes in rainfall distribution. The number of dry days (those with less than 1 mm rain) are projected to increase by about 10 days per year across a broad diagonal band from the southwest to the northeast of the continent, with little change in the southeast and northwest. The intensity of rainfall is projected to increase in most parts of the country, particularly in the north. Solar radiation is projected to remain almost unchanged across most of the country, but there could be small changes (increases of up to 10%) across the southeast and southwest corners by 2070. Likewise, changes in relative humidity are likely to be small with a general decrease across the country that is likely to be greatest in the western interior (2 – 3 % decline by 2070). Potential evapotranspiration is expected to increase across most of the country, with the greatest increases in the north and east (4 to 12 % increase by 2070). Changes in the amount and distribution of rainfall and increases in evapotranspirational demand are projected to increase the incidence of drought with up to 40% more droughts in eastern Australia and 80% more in the south west by 2070 (Mpelasoka *et al.* 2007). Projected changes in wind are highly uncertain, but wind speed is estimated to increase by 2 – 10 % by 2070 on the east coast and southern interior, and to decline by a similar amount off the southern coast. The global sea level is projected to rise 18 – 59 cm by 2100, although uncertain contributions from melting ice sheets could greatly increase this estimate. Mean sea level rise on the east coast of Australia may be greater than the global mean. Increases in sea surface temperatures are expected to be greatest in the southern Tasman Sea (1 – 3 ^{o}C by 2070) and weakest off the south and southwest coasts. Strengthening of the East Australia Current is projected to extend warmer waters further southward. Increases in ocean acidity around Australia are projected to be greatest at mid to high latitudes (> 30^{o}S), where undersaturation of aragonite (a form of calcium carbonate) could occur by the middle of this century. Projections on tropical cyclones are still uncertain with some evidence that the number of cyclones may decline (mainly off the west coast), but the proportion of intense-category cyclones could increase. The risk of hail events may increase along the southeast coast, but may decrease slightly along much of the southern coast. Climate change is likely to influence two important climate processes affecting Australia, the El Niño Southern Oscillation and the Southern Annular Mode (SAM). El Niño events may become drier in southeast Australia and La Niña events may become wetter. Changes in the SAM are projected to weaken westerly winds over southern Australia and strengthen westerly winds at higher latitudes. These changes would also be likely to reduce rain-bringing low pressure systems across southwest Western Australia.

An essential element in adapting to climate change will be to accept the inherent uncertainty in future climate change, including uncertainties in the geographic variation in projected changes. Initially it will be much more important to focus on preparing a suite of adaptation options to encompass the range of projected impacts that may occur, rather than trying to tailor regional and local adaptation strategies to spatially explicit climate change projections.

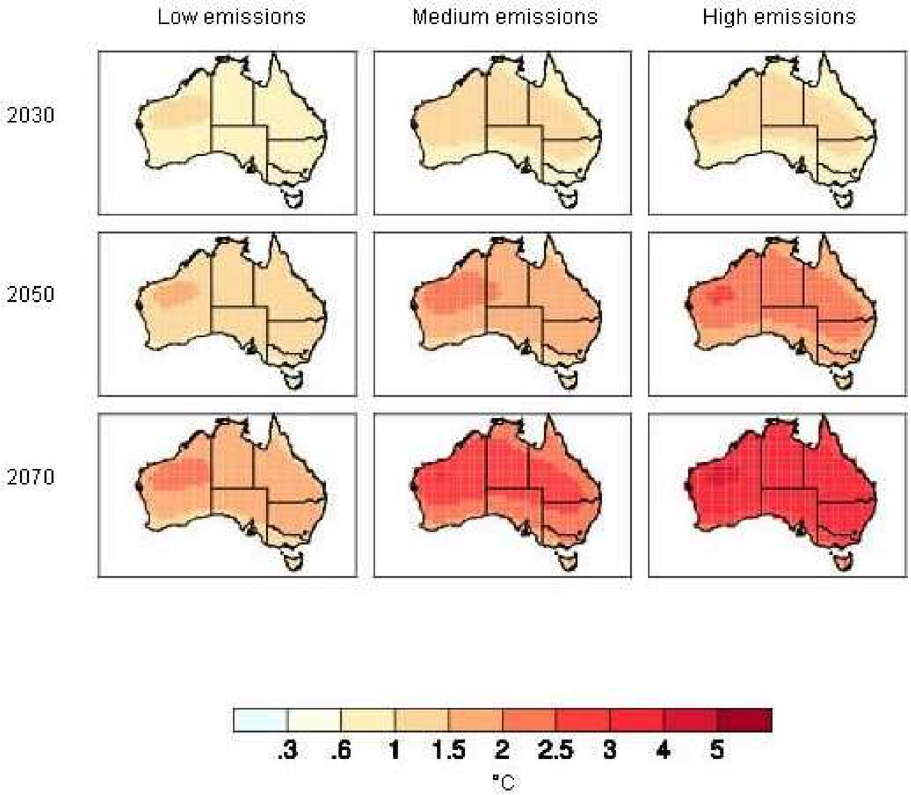


Figure 1.2: Projections of changes in temperature in 2030, 2050 and 2070 relative to the period 1980-1999. Emissions scenarios are from the IPCC Special Report on Emission Scenarios. Low emissions is the B1 scenario, medium is A1B and high is A1FI. (http://www.climatechangeinaustralia.gov.au) (CSIRO 2007)

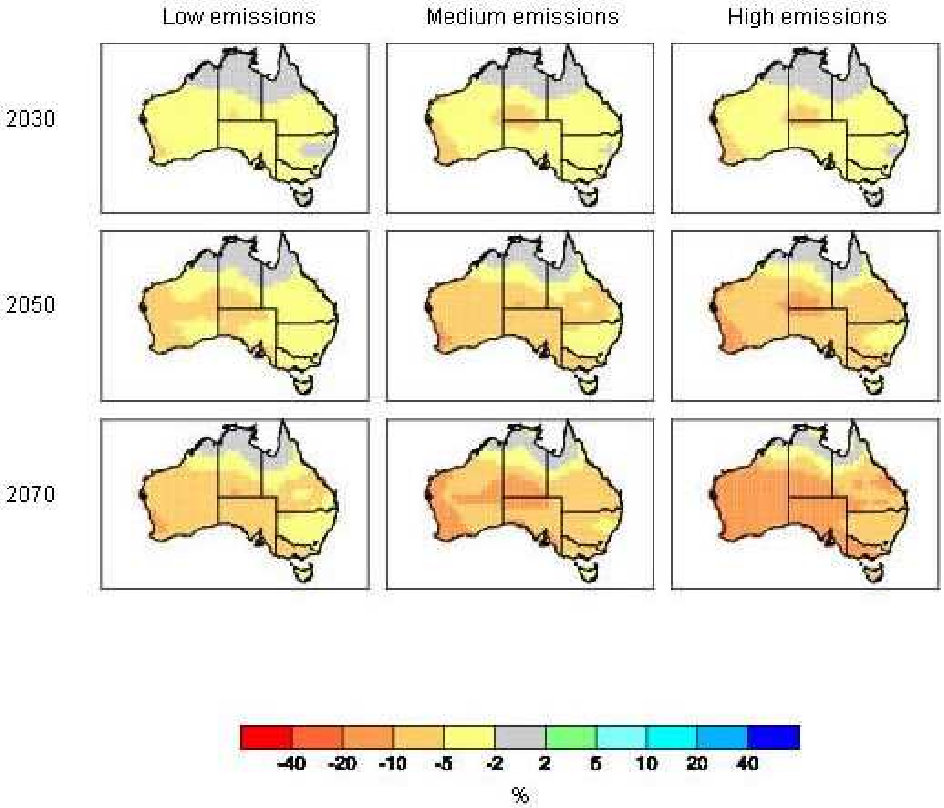


Figure 1.3: Projections of changes in rainfall in 2030, 2050 and 2070 relative to the period 1980-1999. (http://www.climatechangeinaustralia.gov.au) (CSIRO 2007)

Vulnerability and adaptation

Climate models and long-term weather records provide indications of the range of possible types of climate changes that primary industries will have to prepare for in the future. But policy makers and land managers will need to take several other factors into account before the implications of climate change, and the required responses, can be properly understood. First, the impacts of climate change will depend not only on magnitude of changes in climate, but also on the sensitivity of primary industries to those changes. Secondly, the impacts of climate change can be moderated if industries are able to adapt to them, which will depend on both on being able to develop viable adaptation options and communities having the capacity to implement these options. The overall vulnerability of an industry to climate change will therefore depend on the magnitude of climate change, the sensitivity of the industry to these changes, the ability to develop viable adaptation strategies, and the capacity of industries and supporting institutions to implement these adaptation strategies.

All Australian primary industries already have strategies for dealing with the challenges of climate variability. Aside from random inter-annual variation, there are several 'cyclical' climate influences that affect climate variability over periods of several days to several decades (see Table 2.1). In the short-term (< 30 years) it will be difficult to detect trends in climate change because the magnitude of climate change will likely fall within the bounds of random and cyclical climate variability. However, this also means that existing strategies to cope with climate variability already provide some capacity to adjust management practices to track initial changes in climate (McKeon *et al.* 1993). A common strategy across primary industries for adapting to the early stages of climate change will therefore be to enhance and promote strategies for tracking climate variability. There is however some potential for maladaptation in this strategy. At locations where short-term trends from cyclical changes are the reverse of long-term climate change, tracking such short-term changes may leave enterprises in a poorer position to deal with climate change (e.g., central Western Australia is projected to become drier in the future, but rainfall has been increasing over the past 50 years). In such situations, where land managers recent personal experiences of climate change will be at odds with projected future changes, it should also be recognised that there could be a greater reluctance to accepting the projections of climate models and related recommendations for adaptation.

Marginal production areas are likely to be amongst the most vulnerable to climate change. In locations where primary industries are already under financial stress, even slight increases in the severity or frequency of extreme weather events could exceed their capacity to cope. It is these enterprises that are most likely to provide the early warning signs of climate change. It will be important to recognise and identify those most vulnerable areas where the impacts of climate change are likely to exceed the adaptive capacity of existing enterprises. Such situations are likely to require more intensive policy intervention than simply supporting adaptation of existing land uses and could require transformation to quite different types of activities. Such transformative changes in land use should not be viewed only in a negative, reactive way, since climate change may also produce new opportunities where alternative land uses are more productive or desirable than existing ones. In both cases it will be important to recognise where the greatest changes in land use and management practices may be required so that the communities can be supported in dealing with the social upheaval this creates.

The following chapters of this report provide overviews of how climate change is likely to affect each of Australia's main primary industries, the options these industries might use in preparing to cope with climate change, and the uncertainties that need to be addressed to start developing adaptation strategies. Only by preparing in advance will Australia's primary industries be equipped to exploit the opportunities and limit the undesirable impacts that uncertain future changes in climate will bring.

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2: GRAINS

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Key messages

- Adaptations to climate change are likely to be important in Australian cropping systems, with adaptations to moderate climate changes possibly turning a problem into a potential opportunity. With more negative climate changes, the same adaptations may significantly reduce the vulnerability to climate change. In the wheat industry alone, relatively simple adaptations may save the national wheat industry between $100M and $500M p.a. at the farm gate. Further benefits are likely if a wider range of adaptations is practiced but these remain to be evaluated.
- There are a range of technical adaptations such as changed crop management practices, new varieties, altered rotations and improved water management that may, in various situations, have significant benefit. In many cases, these are consistent with existing best management practice for climate risk. However, these practices may need to be modified, enhanced or integrated in different ways to cope with the likely challenges of climate change
- There are also a range of potential adaptations in the decision environment in which farm and associated enterprises operate such as industry and regional development policies, stewardship programs, infrastructure development, industry capacity development programs and other policies such as those relating to drought support, rural adjustment and trade amongst many others. Maintaining a flexible R&D base with the capacity for focussed, relevant and rapid response to the changing needs of the cropping industries was seen as a high priority by the farmer participants in this chapter.
- Maladaptation can occur through both over and under-adaptation to potential climate changes. Effective monitoring of adaptation at a range of scales could help reduce the risks of maladaptation by learning what adaptations work, which do not and why. Assessment to ensure that adaptations do not increase net greenhouse gas emissions is critical.
- There are many adaptations for the cropping industry that are consistent with those in other industries. These are dealt with elsewhere in this report. However, a common need raised by the farmers in this chapter is increasing the accessibility of climate scenario data, providing web-based access from a centralised database that can deliver the climate variables needed at the time and spatial scales of interest, for a range of global climate models and for a range of emissions scenarios with several different climate downscaling methods

- The translation of these climate scenarios into adaptation action will need participatory research with participants across the agricultural value chain. In particular these studies will carry the analysis from climate to biophysical impacts on crops and cropping systems to enterprise level adaptation options to farm financial impacts to regional economic and social impacts (such as via livelihoods analysis) and then through to policy options. Integration and adaptive learning are critical and could occur through social and analytical links back to the enterprise scale.

Introduction

Cropping of various types is the major agricultural activity in Australia with a gross value of about $11,300M p.a. Cropping occurs over an area of some 24M ha distributed from the summer-dominated rainfall region of the central highlands of northeast of Queensland in an arc around southern Australia to the winter-dominated rainfall areas around Geraldton in West Australia. In the western and southern regions, the predominantly cool season rainfall (i.e. autumn to spring) allows cropping of wheat, barley, canola, lupins, oats and other cool-season crops to take place on a variety of soil types – from the sands of WA to the heavy clay soils of the Wimmera in Victoria. In contrast, in the northern regions, cropping is largely restricted to heavier soils with high moisture holding capacity which can store the predominantly summer rainfall so that it is available for the cool season crops. Summer crops such as sorghum and maize can also be grown in these regions. In all regions, the industry is highly sensitive to climate with both wet and dry years causing substantial fluctuations in regional yield and grain quality (e.g. see Figure 2.1). The current year is an example with drought conditions approximately halving yield from the record high levels of the previous years (Figure 2.1). In some regions, irrigation is practiced so as to reduce the fluctuations in production caused by dry years. However, in Australia's many over-allocated river systems, even irrigation is not removing climate risks as reduced allocations are occurring in dry years.

High rainfall years also can cause problems with waterlogging, flooding, rain and hail damage, higher pest and disease loads and intermittent recharge of water to groundwater tables and associated leaching of nutrients.

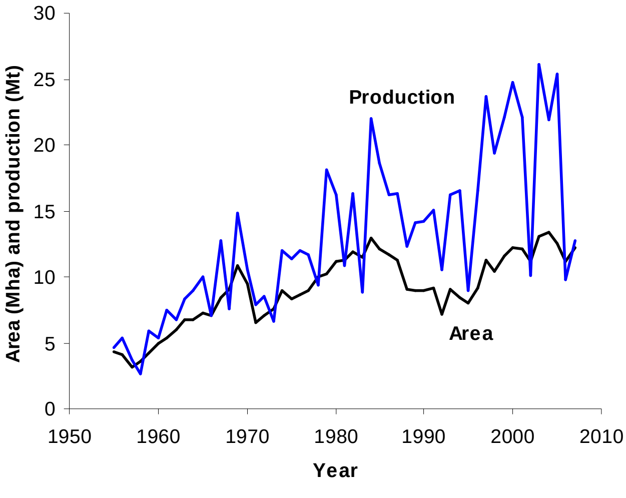

Figure 2.1: Area cropped to wheat (Mha) and wheat production (Mt) in Australia from 1952 to the present. (ABARE 2007).

Grain cropping systems have comparatively high levels of management input when compared with some other Australian rural enterprises such as extensive grazing or forestry. This, in combination with the sub-annual timesteps involved in the management of most crops allows considerable, but not unlimited, latitude for adaptation options to climate change. However, few of these options have previously been comprehensively analysed for Australia. The following sections outline the key adaptation options for cropping systems. The information in these is drawn from the literature and from a small survey sent out to 26 of Australia's top grain-cropping farmers. For this survey, it was necessary to identify likely CO_2 and climate change scenarios. The climate change scenarios for 2030 and 2070 prepared by CSIRO Atmospheric Research (Whetton 2001; http://www.dar.csiro.au/impacts/future.html) were used for this survey. An example of the survey is available in the Appendix (Chapter 13). Whilst there are more recent scenarios now available, the differences between them are small in relation to the variables important for this industry sector.

Adaptation Options

Current Options for Dealing with Climate Variability

Climate in Australia varies over a large range of timescales (Table 2.1) resulting in a large variety of management responses (e.g. Table 2.2).

Recent studies with selected farm managers in Queensland indicate that by using climate information (e.g. seasonal forecasts) in conjunction with systems analyses producers can significantly reduce various risks (e.g. Crimp et al. 2007). By identifying decisions that positively influence the overall farm operation in either economic or environmental terms, these producers have gained a better understanding of the system's vulnerability and started to 'climate proof' their operations. Examples for actions taken when a forecast is for 'likely to be drier than normal' are: maximising no-till area (water conservation), applying some nitrogen fertiliser early to allow planting on stored soil moisture but splitting the application so as to apply some later if a good season eventuates; planting most wheat later than normal to reduce frost risk. In seasons that are likely to be wetter than normal, management options include: sowing wheat earlier; applying nitrogen to a wheat cover crop grown on a dry profile after cotton (normally not expected to produce a harvestable yield) and applying fungicides to wheat crops to minimise leaf diseases (Meinke and Hochman, 2000).

Adaptation to climate changes experienced over the past decades does not happen at the flick of a switch. Changes are subtle and often happen without clear understanding that climate trends are one of the underlying drivers. Frequently, several drivers have to 'push' the system in a certain direction before they result in changed management practice. For instance, while climatic conditions might favour a certain management practice, crop or cropping systems, this will not be acted upon unless costs and prices (i.e. economic drivers) also support these options.

A couple of examples where climate trends have partly resulted in actual changes are illustrated by recent developments in Central Queensland:

Table 2.1: Known climatic phenomena and their return intervals (frequency, in years) that contribute to rainfall variability in Australia. Meinke et al. (2001).

Name and/or Type of Climate Phenomena	Reference (eg. only)	Frequency (approximate, in years)
Madden-Julian Oscillation, intraseasonal	Madden and Julian (1972)	0.1 – 0.2
SOI phases based on El Niño – Southern Oscillation (ENSO), seasonal to interannual	Stone et al. (1996)	0.5 – 7
Quasi-bi-annual Oscillation(QBO)	Lindesay (1988)	1 – 2
Antarctic Circumpolar Wave (AWC), interannual	White (2000)	3 – 5
Latitude of Sub-tropical ridge, interannual to decadal	Pittock (1975)	?? – 11
Interdecadal Pacific Oscillation (IPO) or Decadal Pacific Oscillation (DPO)	Zhang et al. (1997) Power et al. (1999) Tourre and Kushnir (1997) Mantua et al. (1997) Allan (2000)	13+ 13 – 18
Multidecadal Rainfall Variability	Allan (2000)	18 – 39
Interhemispheric Thermal Contrast (secular climate signal)	Folland et al. (1998)	50 – 80
Climate change	Timmermann et al. (1999) Kumar et al. (1999)	???

Table 2.2: Agricultural decisions at a range of temporal and spatial scales that could benefit from targeted climate forecasts (Meinke et al. 2001).

Decision Type (eg. only)	Frequency (years)
Logistics (eg. scheduling of planting / harvest operations)	Intraseasonal (> 0.2)
Tactical crop management (eg. fertiliser / pesticide use)	Intraseasonal (0.2 – 0.5)
Crop type (eg. wheat or chickpeas)	Seasonal (0.5 – 1.0)
Crop sequence (eg. long or short fallows)	Interannual (0.5 – 2.0)
Crop rotations (eg. winter or summer crops)	Annual/bi-annual (1 – 2)
Crop industry (eg. grain or cotton)	Decadal (~ 10)
Agricultural industry (eg. crops or pastures)	Interdecadal (10 – 20)
Landuse (eg. agriculture or natural systems)	Multidecadal (20 +)
Landuse and adaptation of current systems	Climate change

At the crop level, wheat plantings are now 3-4 weeks earlier than in the 1950s (Stephens and Lyons 1998). This is largely the result of a drastically reduced frost incidence in this environment. However, this change was aided by the availability of new wheat cultivars that are well-suited to this environment. Although these changes started to happen in the 1970s and 80s it is only recently that climate trends were identified as one of the drivers (Howden et al. 2003).

At the cropping systems level, Central Queensland has been a summer cropping dominated region. This was a consequence of climatic conditions favouring summer cropping at a time when the region was first opened up to cropping. Recent climatic patterns (since about the early 1980s) do not favour either summer or winter cropping (Howden et al. 2001b). Consequently, cropping systems in Central Queensland have developed into a very opportunistic system, whereby producers can make use of climatic events and rapidly change rotations and summer or winter crops are planted whenever opportunities arise (Pollock et al., 2001). This highlights that cropping systems are to a large extent 'self-adapting', i.e. a string of subtle changes leading to new systems that can only be attributed to climate changes after the event.

At the national level there have been strong trends to earlier sowing times over the past two decades with sowing progressing a day earlier per year on average but greater rates in Queensland and Western Australia (Stephens and Lyons 1998). This appears to be related to the adoption of new herbicide and planting technologies which increase speed of soil preparation and reduce rainfall requirements to sow (Kerr et al. 1992). Earlier sowing dates may also be in response to the strong observed increases in minimum temperatures over this period (Torok and Nicholls 1996) and decreases in frost frequency and duration (Stone et al. 1996). These changes reduce the likelihood of frost damage to early sown crops, thus allowing earlier planting strategies. Nicholls (1997) estimates that this effect plus other more minor climate changes have contributed 30-50% of the observed increase in national yields over the past five decades although this analysis is disputed (Godden et al. 1998, Gifford et al. 1998). Increases in atmospheric carbon dioxide levels may have also contributed to increased yields by an estimated 8% over the past 100 years (Howden et al. 1999d).

Other examples of adaptations are the current debate in relation to opportunistic summer cropping in South Australia and South-East WA in response to recent, uncharacteristic summer rainfall.

In addition to using information on climate variability in on-farm decision making, there are also developing applications in terms of policy and marketing. For example, Hammer et al. (2001) developed a regional commodity forecasting system. It allows the examination of the likelihood of exceeding the long-term median shire yield associated with different season types at the beginning of the cropping season. This system is now run operationally for Queensland and northern NSW by updating the projection each month based on the actual rainfall that has occurred and any change in the SOI phase from month to month (e.g. http://www.dpi.qld.gov.au/cps/rde/xbcr/dpi/Sorghum-crop-outlook-November-07.pdf). Although there appear to be commodity forecasting applications, this system was originally designed to inform government in Queensland of any areas that might be more likely to experience poor crops in any year. This information provides an alert for 'Exceptional Circumstances' issues associated with potential drought in the same manner described for pasture systems in Queensland by Carter et al. (2000). Anecdotal information received from marketing agencies based on their experience with the regional wheat outlook indicate that seasonal crop forecasting in their decision making processes can be beneficial when it is used in addition to their current approaches. Possible decisions to be taken when the outlook is for "likely to be drier (wetter) than normal" are, for instance, forward buying (selling) of grain or shifting of resources from good yielding areas to poor yielding areas.

Adaptation options for the Australian cropping industries to deal with climate change

Many of the management level adaptation options are largely extensions or intensifications of existing climate risk management or production enhancement activities in response to a potential change in the climate risk profile (Howden et al. 2007). For cropping systems there are many potential ways to alter management to deal with projected climatic and atmospheric changes. If widely adopted, these adaptations singly or in combination have substantial potential to offset negative climate change impacts and take advantage of positive ones. For example, in a modelling study for Modena in Italy (Tubiello et al. 2000), simple and feasible adaptations altered significant negative impacts on sorghum (-48 to -58%) to neutral to marginally positive ones (0 to +12%). In that case the adaptations were to alter varieties and planting times to avoid drought and heat stress during the hotter and drier summer months predicted under climate change. When summarized across many adaptation studies globally, there is a tendency for most of the benefits of adapting the existing systems to be gained under moderate warming (<2^{o}C) then to level off with increasing temperature changes (Figure 2.2; Howden et al. 2007). Additionally, the yield benefits tend to be greater under scenarios of increased rainfall than those with decreased rainfall: reflecting the fact that there are many ways of more effectively using more abundant resources, whereas there are fewer and less effective options for significantly ameliorating risks when conditions become more limiting. Overall, the potential benefits of management adaptations are substantial and are similar in temperate and tropical systems (17.9% versus 18.6%). The following sections address management level adaptations in detail.

Varietal change

Temperature increases will reduce the duration of phenological stages of crops, restricting the time they have to accumulate radiation and nutrients. This will generally reduce grain yield thereby tending to counter the yield increase deriving from the CO_2 fertilisation. In Australia it was estimated that, in the absence of adaptive measures, a 1.5 to 2^{o}C increase in mean temperature during spikelet development and grain filling would cancel out the grain yield increase in wheat deriving from a CO_2 doubling assuming that no varietal adaptation was practiced (Gifford 1989, Wang et al. 1992, Howden 2002). Thus, where there is adequate moisture (wet regions or where climate change increases rainfall), there is likely to be advantage in breeding and adopting slower-maturing cultivars (greater thermal time requirements) that could capitalise on the earlier date of flowering and potentially longer photosynthetically-active period before seasonal drought forces maturity. Where there is likely to be both increases in temperature and significant reductions in rainfall (e.g. in the strongly Mediterranean climate cropping regions) it may be advantageous to either keep varieties with similar or earlier-flowering characteristics than are currently used as this will allow grainfill to occur in the cooler, wetter parts of the year (Howden et al. 1999d, van Ittersum et al. 2003) particularly if planting can occur earlier due to reduced frost limitations. Characteristics such as higher response to elevated CO_2 conditions, rapid germination, early vigour and increased retention of flowers in hot/windy conditions may also need to be considered (e.g. Richards 2002). Adoption of the best varietal strategy needs careful evaluation on a site-by-site basis, taking into account changes in both temperature and management. The tools to undertake such assessments are available – but the plant breeding community needs to be better engaged on the issue.

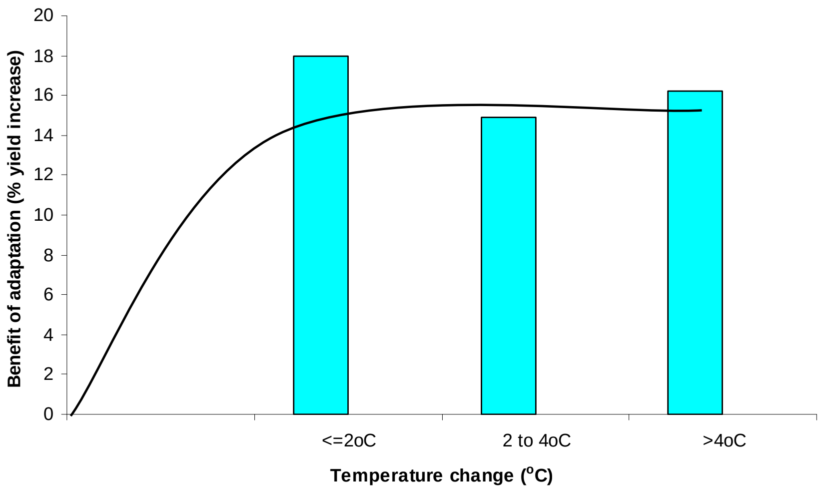

Figure 2.2: Mean benefit of adapting wheat cropping systems to the impact of temperature and rainfall changes calculated as the difference between % yield changes with and without adaptation. The temperature changes have associated changes in rainfall and CO_2 that vary between sites, scenarios and publications. The figures are drawn from a global synthesis of studies, with data from Howden et al. (2007) and the line indicating the change in benefit including the scenario of no change.

The trend towards the incorporation of some vernalisation requirement into modern wheat cultivars will also tend to lock flowering into an appropriate relationship with a progressively earlier spring. Fine-tuning of this relationship would presumably occur over the several generations of varieties that will be developed as climate changes accumulate.

Farmer respondents were particularly interested in enhancing the drought tolerance (e.g. 'staygreen' sorghum) in all existing crops (e.g. spring wheat, grain sorghum, barley, cotton, chickpea, fababean, sunflower, mungbeans etc). Genetic modification may be needed for this as well as non-GM breeding.

Several of the adaptation strategies described below will require interactions with crop breeding groups. Particular issues are ensuring appropriate thermal time requirements, raising grain protein levels in higher CO_2 environments and maintaining pest and disease resistance. A further requirement may be for increased heat shock resistance. Heat shock occurs where there are high temperatures during grain fill (e.g. Blumenthal *et al.* 1991, Stone *et al.* 1996a). These reduce dough-making quality of the grain. Heat shock incidence is likely to significantly increase in northern Australia (1 to 50% increase) with climate change (Howden et al. 1999d). These results would suggest that development of more heat-tolerant varieties would be desirable for cropping regions in Queensland to maintain their capacity to produce high quality wheat. If there is increasing danger of more very hot days, then warnings of changed risk could be helpful in choosing crops that flower outside the key risk periods.

Hotter and drier conditions are likely to reduce the dry-down time prior to harvest and this also may affect final quality (e.g. grain cracking and small grains) requiring either breeding or management adaptation.

Species changes

Higher temperatures may enable the use of summer-growing grain and pulse species such as sorghum in temperate regions where these are not currently used in rotations. The negative impact of a reduction in rainfall is likely to be greater for rotation systems than for single crop systems as there is not a fallow in which to store soil moisture (Howden et al. 1999f). This will impact particularly on crops that show sensitivity to dry conditions such as canola and certain pulses. Furthermore, in rotations, options to vary planting windows are restricted, reducing flexibility to adapt management. Nevertheless, gradual adjustment of rotations will occur to minimise risk and maximise return. This will be aided by effective monitoring of soil moisture and nutrient levels, effective decision support systems, improved seasonal climate forecasting and continuing improvements in the crop management activities (i.e. zero till, wide rows, low plant populations etc) that have relatively recently expanded planting options. If there is less frost risk, earlier spring plantings of warm-season crops may be possible provided that there is follow-up rain after the anticipated drier spring seasons.

Increased temperatures mean that cotton may also be able to be grown further south than currently (if adequate water is available) providing new rotation options in those areas with suitable soils (see Chapter on cotton). However, the issue of water availability is likely to be a key one as the climate change forecasts are for greater reductions in mean flows in the catchments in the southern part of the Murray-Darling Basin than in the northern part.

If there is reduction in rainfall and increased rainfall variability, it will make dryland cropping less attractive and there is likely to be consideration of a change to a greater proportion of stock in the farm business. A reduction in the production of annual pastures and crops could be offset by a greater planting of perennials such as lucerne that would be able to make use of summer rains and generally all available soil moisture. This will tend to extend the duration of rotations. The use of summer forage crops may increasingly be employed after any significant summer rains – in regions with soils of low water holding capacity (i.e. much of WA) there may be a need for varietal development to increase the reliability of this option. However, livestock are also subject to the impacts of drought – a key message from some of the farmer respondents being a strategy of early removal of stock from pastures to finish them in a more managed environment (using local grain to add value to the product). These options may become more important under climate change.

Planting time variation

Higher temperatures are anticipated to reduce frost risks, particularly if the realised temperature change is mostly increases in minimum (night-time) temperatures as has happened over the past five decades (e.g.Wright et al. 1996). Reductions in the duration of the frost period may allow earlier planting (a month or more earlier) and consequently increased yields as grainfill is more likely to occur in the cooler months when the likelihood of water stress is lower (Howden et al. 1999d, van Ittersum et al. 2003). This may require concurrent changes in thermal time requirements of the varieties used depending on any changes in planting dates. There is evidence that farmers are already planting earlier in response to lower frost risk (e.g. Stephens and Lyons 1998) and that this is enhancing yields (see section on current management of climate).

The above adaptation of earlier planting assumes no change in the timing of ‘autumn break’ rains or of availability of stored soil moisture - both of which could be affected by climate change. The effect of climate changes on the autumn break have not yet been investigated, however, the greater likelihood of reductions than increases in future autumn rainfall in cropping areas in WA, SA, Victoria and southern NSW (CSIRO 2007) suggest that the autumn break may be postponed compared with historical experience. Consequently, there may need to be ongoing re-assessment of planting rules in these regions in conjunction with varietal changes. The rainfall scenarios for cropping regions in Qld and northern NSW where stored soil moisture is critical are not quite as negative as for southern Australia suggesting that planting decisions need to continue to be sensitive to stored soil moisture levels and seasonal climate forecasts.

Crop management (spacing, tillage, fallows, rotations, irrigation)

There are many crop management practices that could be used in specific circumstances to lower risks from changed climate conditions (e.g. Easterling et al. 2007). These include:

- adopting zero-tillage practices (especially if there is increased rainfall intensity as greater infiltration will be needed with fewer but heavier events)
- develop more minimum disturbance techniques (i.e. seed pushing, all weather traffic lanes which allow planting while raining)
- using reactive strategies to track climate variation on daily or seasonal time steps. For example crop planting decisions such as timing core, cultivar, fertiliser rates can be based on soil moisture stores, nutrient concentrations and average seasonal rainfall (Hammer et al. 1996) and financial and commodity forecasts. For example, there are simple analyses in Australian Rainman and more comprehensive analyses using cropping systems models such as APSIM run operationally by many farmer groups such as the Birchip Cropping Group
- extending fallows to effectively capture and store more soil moisture (suitable mostly with heavy soils)
- planting later in the season when enough water in profile to get a crop.
- widening row spacing or skip-row planting
- lowering plant populations
- staggering planting times
- developing efficient on-farm irrigation management with effective scheduling, application and transfer systems
- reducing losses from irrigation systems during water transfers through improved channel lining etc
- monitoring and responding rapidly to emerging pest, disease and weed issues, noting that support of effective RD&E would be needed
- assessing fertiliser inputs. For example, the climate change scenarios in situations where soil nitrogen is high will tend to increase the risk of crops ‘haying off’ resulting in subsequent major reductions in effective yield.

However, most of these have yet to be analysed for their benefits under climate change although such assessment is now underway. It is likely that the benefits will be quite context specific and involve trade-offs. For example, wide row and skip row plantings can increase yield stability and particularly increase yield in poor rainfall years. However, they also reduce ground cover, water storage at the end of the fallow and infiltration whilst increasing runoff and soil loss.

Nutrient management change (fertilisation and rotations)

There is a premium for high levels of protein in various crops (e.g. durum wheat, malting barley). Increases in atmospheric carbon dioxide levels are likely to result in declines in grain nitrogen and hence protein and flour quality with a doubling of CO_2 (e.g. Rogers *et al.* 1998; Fangmeier *et al.* 1999). However, the amount of reduction varies with cultivar (Rogers *et al.* 1998) and N-supply to the crop. With ample N-status the decline in grain protein may be small (Kimball *et al.* 2001) however, in many cases, grain crops in Australia do not have ample nitrogen and so there is a risk of reductions in grain protein. To maintain grain nitrogen contents at historical levels, there may be a need to considerably increase the use of legume-based pastures (e.g. extending rotation length to have a longer pasture/legume phase), increase use of leguminous crops or further increase nitrogen fertiliser application (extending an existing trend to higher applications: Hayman and Alston 1999). There will also be a need to continue monitoring soil nitrogen concentrations and to breed higher protein cultivars or cultivars that are resistant to decline in grain protein with increasing atmospheric CO_2 concentration. The risks of higher CO_2 on grain protein will compound those arising from long-term rundown of the nutrient status of cropping soils (e.g. Dalal et al. 1990, Hamblin and Kyneur 1993, Verrell and O'Brien 1996). Farmer respondents noted that whilst there recently had been rapid increase in understanding of nitrogen management in cropping systems there remained a need for better technologies (e.g. direct delivery of ammonium solutions into the root zone with minimal soil disturbance), improved monitoring and enhanced education. The farmers considered that higher levels of CO_2 and possible increases in climate variability just make these even more needed. They also noted that marketing adaptations may be to respond to increased demand for low protein grain as stock feed. There are options to compensate for low protein levels by alterations to the stock rations. Biofuels are another prospective option, but farmer respondents were concerned about the implications of a more variable climate for reliable provision of bio-fuel feedstocks.

The adaptations of fertiliser application and change in rotations will have their own impacts on soil acidification processes and water quality in some regions, the ratio of sown pasture to crop in the mixed farming system and on farm economics. Furthermore, such adaptation could be a significant source of greenhouse gas emissions as production, packaging and distribution of nitrogenous fertiliser generates about 5.5 kg CO_2 per kg N (Leach 1976) and as both fertilisation and legume rotations increase emissions of the potent greenhouse gas nitrous oxide (Prather et al. 1995).

Grain protein contents are likely to remain sensitive to temperature and soil moisture availability during grainfill as at present (i.e. dry and hot finishes to a crop tend to increase protein levels). Consequently, in some regions, there may be factors that partly compensate for or exacerbate the effects of carbon dioxide levels on grain quality. For example, increased water stress during late grainfill can increase grain protein contents whilst conversely there are a range of climate-influenced situations which can reduce grain protein (e.g. nutrient leaching, poor early vigour limiting plant nitrogen pools, high rainfall during grainfill). Alternatively, some growers are already targeting a premium market in biscuit wheat which requires low protein, soft wheat varieties. However, there are currently few other such markets with low protein hard wheat generally being sold at the lower end of the market. Given that high CO_2 will be global in its extent and impact, the prospects for maintaining a premium soft wheat market seem to be limited as all producing nations are likely to be grappling with how to maximise returns from lower protein wheats.

Farmer respondents suggested that support of breeding programs was needed so that they have the varieties available to tackle the issues of protein level (e.g. a wheat that fixed its own nitrogen would be good). Also that government policy needs to 1) ensure that the industry is structured so it can readily adapt to the changing needs of the market from 'paddock to plate', 2) that can also explain to the customers the problems that climate change is causing or 3) find new customers such as biofuel plants. They viewed an integrated structure of the grains industry (from grower to marketer) was important in achieving appropriate responses to climate change.

Erosion management

Rainfall intensity is anticipated to increase with climate change even under scenarios where average rainfall may decrease (e.g. Whetton et al. 1993) continuing the current trends to higher intensity rainfall events in Australia (Suppiah and Hennessy 1998). This is likely to increase risks of soil erosion, particularly on soils with high erodability (e.g. solodised soils). Key adaptations may be:

- increase residue retention and to maintain crop cover during periods of high risk so as to reduce raindrop damage on the soil surface and to allow for water to infiltrate
- to maintain erosion control infrastructure (e.g. contour banking etc)
- to adopt controlled traffic systems up and down slope

These actions are already generally implemented in cropping systems (at least by farmers who have a focus on NRM) but their importance is likely to increase over time. Improved warning of seasonal conditions with high erosion potential would enable improved risk management.

Management to reduce water-related soil erosion will also tend to reduce risks from wind erosion if this increases.

Salinisation management

Increased rainfall intensity (and high CO_2 levels) may also increase drainage below the root zone – the driver for dryland salinisation (Howden et al. 1999e, van Ittersum et al. 2003). This will be particularly prevalent on lighter-textured soils. Indicative changes under a doubling of CO_2 alone are for a 6 to 20% increase (Howden et al. 1999e). This would represent a substantial potential change in landscape hydrology which is likely to increase risks of salinisation in areas not yet affected and increase rates of these processes in areas already undergoing this form of degradation. This increase may be more than offset in some regions if there is a reduction in rainfall in autumn and winter. For example, the strong drying trends across southern Australia would suggest between 30 and 80% reduction in drainage components depending on site (van Ittersum et al. 2003). Such large reductions in drainage would have significant implications for catchment management and policy development for addressing the dryland salinisation issue. In addition, the large reductions in farm profitability that may occur with climate change in Western Australia may significantly reduce the capacity of individual farmers to implement practices (such as establishing perennial plants) to reduce dryland salinisation risk (Johns et al. 2005). The balance between these opposing tendencies is not well understood. In contrast, in north-east Australia, the tendency will be to increase drainage, increasing salinity risk (Howden et al. 1999e), Hence, policies relating to dryland salinisation need to take the potential impact of climate changes into account and may need to be adapted over time in conjunction with climate change and its effects on hydrological processes and farm profitability.

Moisture conservation

Changes in evaporation and vapour pressure deficit (VPD: the difference between the moisture content of the air and its potential moisture content at that temperature) are important for transpiration of water from plants, evaporation from soil and water storages and for the efficiency of water use by plants. Evaporation and vapour pressure deficit are affected by temperature (e.g. Tanner and Sinclair 1983; McKeon et al. 1998). However, the way in which they may change in the future is highly dependent on the way in which daytime and night-time temperatures change as well as changes in wind speed. If we assume that the change is symmetrical (i.e. the rate of change is similar for both night and day temperatures) then there will be a significant increase in evaporation (about 3% per ^{o}C) and VPD (about 6% per ^{o}C). If the past trend of greater increases in night-time temperatures than daytime temperatures continues at approximately the same ratio (0.85 *vs* 0.39^{o}C: Wright et al. 1996) then there will be little change in average evaporation or VPD. However, GCM (global climate model) analyses are as yet uncertain as to future differential day-night warming or changes in vapour pressure (Le Truet 1999).

If we assume that temperature changes will be symmetrical (and hence evaporation and VPD increased) then efficient moisture use can be enhanced by:

- increasing residue cover (maintaining stubble) particularly in association with minimal or no tillage
- increased efficiency of water use can be achieved through planting and phenology that maximises growth during the cooler, wetter months when VPD is low and by the development of varieties with higher water use efficiency
- by establishing crop cover in high loss periods so that any water transfer at least results in crop growth
- weed control
- by maximising capture and storage of excess rainfall on-farm perhaps by incorporating raised bed technologies into controlled traffic operations and directing flows into storage zones. This may be especially important if rainfall intensity increases. Farmer respondents noted that such a substantial change in cropping system design may require appropriate government policies.

The effects of higher VPD on transpiration rates will be countered to varying extents by the reduced stomatal conductance under elevated CO_2 concentration.

In some areas, such as the higher rainfall parts of the WA wheatbelt, waterlogging and nitrogen leaching are problems. Consequently, the drier rainfall scenarios out to 2030 may result in beneficial impacts. However, further reductions in rainfall to those in the 2070 scenarios would result in soil moisture shortages requiring adoption of moisture conserving strategies.

In irrigated crops, higher evaporation rates and higher VPD will mean there is potential for greater water use per unit production – at the same time as there may be reductions in water allocation due to reduced river flows. Hence, key adaptations may be to ensure access to water and to increase water use efficiency (i.e. reduce leakage and leaching, reduce soil and on-leaf evaporation, maximise transpiration). Both of these are a current focus of industry due to water reforms, allocation, pricing and degradation of natural resources. The focus will perhaps need to be further sharpened.

Use of seasonal forecasting

The El Niño-Southern Oscillation system (ENSO) is a key source of variability in rainfall and wheat yield in Australia (e.g. Rimmington and Nicholls 1993). ENSO impacts are largest on Australian winter and spring rainfall and temperatures. El Niño events are associated with reduced rainfall across much of Australia and are known to adversely affect crop production, particularly in north-east Australia (e.g. Stone et al. 1993, 1996b, Hammer et al. 1996). La Nina events tend to have higher rainfall and hence higher yields but they may also result in greater incidence of waterlogging, crop spoilage and pest and disease problems. There is a developing view that climate change may result in increased incidence of El Niño and possibly La Niña events (e.g. Meehl and Washington 1996, IPCC 2007) but further improvement in ocean-atmosphere modelling is needed before confidence can be increased in such projections. One possible beneficial outcome from such changes in the frequency of El Niño/La Niña events is that this may assist crop management by increasing the frequency of years in which seasonal forecasting can be used to guide crop management (eg Meinke and Hochman 2000, Gifford et al. 1996).

Following early demonstrations of the value of using statistical seasonal forecasting in cropping management decisions (e.g. Clewett et al. 1991), there has been widespread adoption of this information (Meinke et al. 2006). If the relationships between local weather and these broadscale factors (e.g. the Southern Oscillation Index or regional sea surface temperatures) remains largely stable, then the continued use of statistical seasonal climate forecasts provides a key way for agriculture to 'track' climate changes (McKeon and Howden 1992; McKeon et al. 1993; Gifford et al. 1996). Process-based forecasts using coupled ocean-atmosphere models hold out the prospect of improved forecasts which will automatically incorporate the climate changes (Meinke et al. 2001). If forecast accuracy can be improved then there may even be a broader range of landuses at a given location that can be chosen so as to adapt to climate change. Utility of this information could also be enhanced by development of alternative farm enterprise plans depending on the forecasts taking into account the different benefits, costs and resources in each. Farmer respondents suggested that significant improvements in the reliability of seasonal forecasting would revolutionise the industry allowing better tailoring of decisions to achieve specified outcomes.

Decision-making using seasonal forecasts is improved if allied with on-ground observations such as soil moisture content at planting (e.g. Crimp et al. 2007 also see following section on monitoring/evaluation) which is already a critical input into planting decisions especially in regions with heavier soils. Lessons learned from the adoption of seasonal climate forecasting into decision making can now be used to address climate change issues (McKeon et al. 1993; Meinke et al. 2001). This requires a) further improvements in dynamic climate modelling tailored towards decision making in agriculture, b) continued investment in cropping systems modelling and quantitative approaches to risk management and (c) improvement in our understanding and predictive abilities in relation to pest and disease management.

Irrigation

Irrigation is one way to reduce climate risks by removing water limitations to crop growth. However, both existing and proposed changes to the way in which water rights are managed and traded have significant implications for the irrigated cropping sector that may, under some proposals, result in seasonally-varying allocations. This will introduce elements of climate risk back into the sector.

Scenarios of climate change indicate substantial reductions in mean flows but higher flow variability in Australia (Arnell 1999 and see the Water Resources chapter) at the same time as possibly increased evaporative demand, indicating that climate change will greatly increase that risk, particularly where water rights are expressed as a proportion of flow. The current period of low water allocations is increasingly being seen by industry as potentially presaging conditions that may be more frequent under climate change.

Farmer respondents stated that traditional irrigated cropping will be increasingly more market driven by having to meet long term supply contracts. These contracts will be written to assure the buyer of a supply of consistent specified-quality produce (often for niche markets beyond conventional broadacre cropping e.g. human consumption pulses, vegetables, plants with medicinal qualities) and provide the producer a satisfactory long term pricing arrangement. Stable supplies of irrigation water would be a pre-requisite and consequently management of climate change may need the establishment of water trading arrangements (e.g. equivalent to forward selling) to cope with the possible change in flows and variability. In such a case, profitability will need to be more dependent on return per megalitre of water (rather than per hectare) and information sources will need to be upgraded to facilitate effective decision-making. With water becoming more critical, there will be a need for further improvements in water distribution systems (to reduce leakage and evaporation), irrigation practices such as water application methods, irrigation scheduling and moisture monitoring. Shorter season varieties of summer crops may be necessary to avoid the increased chance of weather damage at harvest in the autumn especially in light of the suggested increased intensity rainfall. These shorter season varieties should also have a lower total water requirement.

Monitoring and evaluation

An important proactive step for producers to adapt to a changing climate is to maintain a thorough measurement and analysis program of their own local climate and production systems to compare with climate change scenarios (Gifford *et al.* 1996). Linked with this activity could be a national service to maintain farm instrument calibration, collate farm weather records and interpolate them in relation to the meteorological station records, and provide software and advisory service for interpretation of the data in relation to seasonal weather forecasts, farm production and predictions of climate change. Such proactive climate data acquisition and interpretation at the farm level could provide the capacity for reactive and opportunistic adaptive measures by farm managers. Parts of such a system already exist, for example with the Silo database (joint QDNRM and Bureau of Meteorology supported by MCVP) that can provide an interpolated climate record for any point in the nation, the AussieGrass project (established by the Climate Variability in Agriculture Program) that provides spatial assessment of grazing systems across the nation and the Australian RainMan decision support package. There are many other activities that could contribute to this goal but largely remain uncoordinated and unlinked to climate change adaptation.

Management of pest and diseases

Pest impacts on crops are widespread and costly to industry, and include many trade access issues for grains and pulses. Many of the pests such as *Heliothis* moths, armyworms, sucking bugs, diamond backed moths (on *Brassica*)) respond strongly to climate signals and their impacts are very dependent on climatic variability.

Adaptations to climate change are likely to happen *via* increased understanding of impacts and potential responses of recent climate variability manifestations (last 20 years) and are best delivered via the two key emerging strategies: (a) integrated pest management and (b) area-wide management (i.e. coordinated responses of growers and policy makers across an entire region).

Many of these tools rely on either intensive monitoring or on computer simulations of pest numbers to flag high-risk periods for each species of pest. The latter are poorly developing in Australia compared with our competitors overseas (one of the most successful in the USA uses Australian software!). A large proportion of growers choose to apply excessive amount of chemical as 'insurance treatments' often because they do not have ready access to reliable information on the risks to the crop.

Similarly, many diseases are strongly influenced by climatic factors and so are anticipated to alter with climate change. Some of the diseases which may alter are Take-all (*Gaeumannomyces graminis*), which is a fungal disease that causes major crop losses when there are extended periods of high soil moisture. Its severity may be reduced if there is an increase in rainfall variability and drier winters as suggested by recent climate change scenarios for southern Australia. The development of stripe rust (*Puccinia striiformis*) is highly sensitive to temperature increasing with temperatures up to 16^{o}C then declining with further warming. The amount of stripe rust and yield losses is dependent on temperature during grain filling such that a temperature rise may increase the amount of stripe rust but not necessarily mean additional yield losses. Current climate change scenarios suggest the changes in impact of this rust will vary regionally, with management and with cultivar. Septoria blotch (*Septoria tritici*) incidence is affected by the time of sowing and the amount of rainfall at heading. The current scenarios of reduced rainfall over southern Australia (less severe infection) but increased temperature (more severe infection) result in an uncertain outcome. Viral diseases such as Barley Yellow Dwarf, which rely on transfer by aphids, may increase with warmer winter temperatures. Climate change may also affect the balance between soil-based pathogens like *Fusarium graminearum* and their antagonists such as *Trichoderma* but again, outcomes are uncertain. Elevated CO_2 concentrations may also increase the fecundity and evolution rate of anthracnose (*Colletotrichum gloeosporioides*) and other pathogens (Chakraborty and Datta 2003) whilst temperature increases can increase pathogen development and survival rates, disease transmission and hoist susceptibility (Harvell et al. 2002).

Summer rainfall could also be a problem with weed (volunteer cropping) species providing 'green bridges' for the diseases of our winter crops and this would necessitate their control in the summer months with spraying or grazing.

Current management practices that respond to, or override, climatic variability include:

- Genetic modification of crop plants to create insect or disease resistant and herbicide tolerant varieties (plant breeding and GMOs)
- Importation of exotic natural enemies of pests that were previously introduced without them. Also repeated, mass (inundative) releases of parasitic wasps to control insect pests.
- Isolation and propagation of local natural enemies/diseases (e.g. *Metarhizium* on locusts, termites)
- Cultural practices such as crop rotations, mixed crops, use of physical barriers to reduce disease transmission
- Chemical pesticides and increasing bio-pesticides (e.g. Bt) and bio-fumigation of soils using *Brassica sp* as alternate crops

- Monitoring and use of predictive models to improve timing of interventions to coincide with high risk periods.
- Landscape scale-management involving groups of growers cooperating to reduce communal threats. e.g. when growing melons in rotation with soya beans or sugar, or chickpeas mixed with cotton.

These generally will need to be fine-tuned so as to cope with new challenges arising from climate change. Farmer respondents noted particularly their existing reliance on research and development and the likely need for increased R&D to cope with climate change. There may also be a need for the development of new crops to use in rotations. Climate change may also reduce the frequency of conditions suitable for spraying insecticides, herbicides and fungicides, requiring alterations in spray technologies and practices (Howden et al. 2007b).

Under climate change the seasonal timing and magnitude of pest and disease outbreaks will change and effective responses will need to be based on improved understanding and more reliable indicators. Specifically, better indicators are needed of successful over-wintering of a wide range of insect pests and plant diseases. This could then be fed into phenological models and GIS that are applicable around the country (i.e. producing geographical scale outputs in real-time).

There will be a need for enhanced communication to make farmers aware of the nature of any imminent pest and disease risks and effective options for their control. A continuing commitment may be needed from Agricultural Protection Boards, State governments and Shire Councils to extend their commitment to controlling listed weeds and pests and control volunteer crop species on road verges and Crown land to prevent disease build-up. Improved engagement on climate change issues by groups such as Plant Health Australia and Animal Health Australia could assist.

R&D and education

Farmers cannot conduct controlled experiments to assess different management alternatives in an ever-changing environment. Instead, a key adaptation at the national level would be public sector support from a vigorous agricultural research and breeding effort, channelling experimental information into cultivar, breeds and technological and management alternatives. Complementing this would be an agricultural advisory network capable of interpreting property specific climate records and production in terms of research findings. Mechanisms are needed also to ensure that farmer innovations for adapting to climate change are linked back to the R&D groups for evaluation. Farmer respondents noted that they needed to be ready to adapt – to have the market information and R&D either in place or streamlined for rapid responses.

Farmers in ‘core’ cropping areas may be also able to learn much from those in currently marginal areas in terms of dealing with moisture limitations, nutrient and residue management and disease management.

The farmer respondents considered that:

- continuation of the public/private funded varietal breeding programs with access to global gene pools was needed to meet the new challenges of reduced rainfall and higher temperatures (with or without GM crops) including

- a continuing commitment to research was needed by organizations such as the GRDC and CSIRO into areas such as cropping systems management
- maintenance of a research base was important so that all the scientific tools will be available
- continued investment in organizations such as the Bureau of Meteorology, CSIRO and State Agencies such as the Queensland Department of Primary Industries and Forestry and SARDI (South Australian Research and Development Institute) which are world leaders in dealing with climate forecasts of different types and their use in agricultural decision-making.
- if variability in the farming environment increases as a result of climate change then there may need to be a revision and modification of existing policy instruments that support financial viability over the longer term (e.g. farm drought bonds)

Research information needs to be substantiated with 'real life' trials and scenarios. For example, the on-farm demonstrations activities of farmer machinery and practice by groups such as the Birchip Cropping Group and the Topcrop program. Such activities ensure that the information is relevant and delivered to the user efficiently.

Some farmer respondents were concerned about the implications of climate change in relation to maintaining a viable regional Australia not just viable farming. For example, the implications of climate change for small regional business and the adaptations that they will need. Farmers also thought that governments need to move away from ‘handouts’ that occur in dry years and encourage/offer incentives to small business to manage variability and change for themselves. The respondents thought that a safety net system based generally around Exceptional Circumstances for extreme events is still needed but with much stricter guidelines than are currently in place – some farmer respondents noted that poor (or aggressive) management was still being rewarded whilst ideally government support should be directed to those farmers who work to manage climate risks effectively. Some suggestions were for the guidelines to include more training to improve self-reliance.

Land use change (infrastructure, knowledge base)

Regional land use patterns are strongly affected by climate. Hence, changes in climate would indicate corresponding changes in land-use (e.g. Howden et al. 2001a,b, Ramankutty et al. 2002). In some cases, this could mean retreat of cropping zones from the dry margins and in others possibly expansion into either marginal zones in the north (i.e. Mitchell grass downs) or the wetter margins outside the current southern cropping zones (Howden et al. 1999d, Reyenga et al. 1998, 1999a, 2001). The increasing water use efficiency from increasing atmospheric CO_2 is expected to have particularly strong effects on crop productivity at the dry margins (e.g. Gifford 1979, Ramankutty et al. 2002) but this effect can only compensate for lower rainfall to a limited extent and extremely dry conditions will still result in very low yields. If the more extreme climate change scenarios eventuate, it may become necessary to switch land use systems completely; for example from mixed farming to solely grazing or to water catchment or plantation forestry in some areas. Governments may have a role in monitoring land use and fostering change when necessary (e.g. via industry restructuring) taking into account potential competing uses (e.g. nature conservation, environmental stewardship) and dealing with potential conflict. For such large-scale adaptation, in addition to transitional support, there will likely be a need for a continuing education plan to retrain producers in new enterprises and to maintain flexibility in adapting to new circumstances. These needs are only marginally different to those existing needs for increased management skills and fostering flexibility in agriculture. Infrastructure changes may also be needed to meet transport and processing changes if there is substantial landuse change (e.g. Hayman and Alston 1999).

Another aspect of rationalisation of agriculture may be increasing farm sizes to increase economies of scale - as has been happening for decades. One farmer respondent noted that there may be an increase in the proportion of corporate to family-owned farms as the large corporations will likely have the financial reserves to get through adverse climate periods and adaptation transitions.

Financial institutions and trade

Lending policies of financial institutions can greatly constrain options for producers to adjust their operations in the light of change. Lending institutions may have to change their policies to take account of predicted changes in the circumstances of their customers: information needs to be supplied to both the financial and farming industries. Support (and education) of approaches such as forward selling may be a constructive role for the sector.

Increased use of crop insurance is one possible adaptation but recent rapid rises in insurance premiums have (at least temporarily) made this problematic. There are actuarial issues that may arise in assessing risks in a changing climate as distinct from the historical risk assessment approaches conventionally adopted in the industry. The conventional approaches by definition will provide a poor assessment of future risk. The insurance industry is pro-active in assessing climate change consequences and may be in a position to provide insurance products for agriculture.

Climate changes will also affect our trade competitors. The limited global analyses available so far on this suggest that there may be new cropping land viable in the northern hemisphere as a result of climate change but little in the tropics, that the negative effects of higher temperature (especially when it exceeds about $2^{o}C$) are likely to be pervasive across the equatorial to mid-latitude cropping belts and that the USA, South America, South Africa, India and China are all likely to be negatively impacted by rainfall reductions (Ramankutty et al. 2002, Easterling et al. 2007). The net effects of climate change interacting with improvements in productivity on global grain production are likely to approximately balance for some decades but then tend towards the negative (Tubiello and Schmidhuber 2007). A capacity to assess the ongoing production prospects of market competitors as well as the factors driving demand may assist Australian industry and government policymakers in framing their own responses to climate change more effectively.

Risks of Maladaptation

Maladaptation can occur through both over and under-adaptation to potential climate changes. Indeed, it could be argued that given the uncertainty associated with climate change, then some degree of maladaptation is inevitable. Effective monitoring of adaptation at a range of scales could help reduce the risks of maladaptation by learning what adaptations work, which do not and why (Howden et al. 2007).

Maladaptation can also arise through unintended negative consequences either inside or outside the agricultural value chain. For example, it is important to ensure that adaptations themselves do no lead to increased net greenhouse gas emissions such as might occur if there is increased application of fertiliser nitrogen to offset reductions in grain protein and to enable full response to rising atmospheric concentrations of CO_2. As noted in the following section, such an adaptation could lead to significant emission of greenhouse gases as well as a range of other on-site and off-site impacts. However, at the moment, there is no comprehensive analysis of these types of maladaptations. Consequently, a significant benefit from adaptation research on cropping systems may be understanding how short-term response strategies (e.g. peri-urban development in high rainfall areas potentially suitable for agriculture) may link to long-term options (e.g. landuse change) so as to make sure that, at a minimum, management and/or policy decisions implemented over the next one to three decades do not undermine the ability to cope with potentially larger impacts later in the century.

Costs and benefits of adaptation

Many of the adaptations required for adapting to climate change are extensions of those currently used for managing climate variability (e.g. Howden et al. 2007). The goals of such existing management strategies are usually to deliver on one or more aspects of the ‘triple-bottom line’ (i.e. economic, environmental and social outcomes). As such, the adaptations generally have immediate application as well as relevance to adapting to climate change. What is known of the benefits of adaptation to productivity and sustainability of cropping systems has been outlined in the previous section. In terms of making some assessment of the direct costs and benefits of adapting to climate change, there remain few studies to date in Australia. In particular, adaptations always have some costs and these are often overlooked (Scheraga and Grambsch 1998).

The national financial benefit to the wheat industry of a subset of the possible adaptations to climate change have been assessed by Howden and Jones (2001, 2004) and Howden and Crimp (2005) using risk analysis approaches. The adaptations were varietal change and alteration of planting windows – key adaptations previously explored with farm level gross margin analyses by Howden et al. (1999d). Just these two adaptations could save the national wheat industry between \$100M and \$500M each year (in current dollar terms) by maintaining productivity in the face of change. These adaptations changed the mean result from being negative (on balance of probabilities) to positive. Clearly, investment in adaptation is extremely worthwhile for the wheat industry. However, in that study there remained a large negative ‘tail’ of results resulting from very dry and hot climate change scenarios: hence adaptation cannot remove all the risk from climate change. Furthermore, since those analyses, the newer climate change scenarios have increased the probability and degree of serious negative climate change (CSIRO 2007). If such changes eventuate, additional adaptations such as those identified in the previous section of this chapter could further significantly reduce the negative impacts of such changes – at least in most regions. However, comprehensive assessment of the benefits of adaptation options remains to be undertaken.

At the farm level, Howden et al. (1999e) assessed adaptations of fertiliser addition to maintain grain nitrogen contents at historical levels. They found that there will be a need to increase application rates by 40 to 220 kg/ha depending on the future climate and CO_2 scenario and location (Howden et al. 1999e). Optimum fertiliser application adaptation for a given scenario increased gross margin by about 20 to 25% (e.g. Figure 2.3). However, at higher levels of fertiliser applications, the increased cost of fertiliser was not offset by increased income (i.e. the strategy became maladaptive) with this level of fertiliser application being lower in drier regions and higher in wetter regions. Furthermore, such adaptations of increased fertiliser use will have their own impacts on soil acidification processes and water quality in some regions and on farm economics. These were not costed. Furthermore, such adaptation could be a significant source of greenhouse gas emissions as production, packaging and distribution of nitrogenous fertiliser generates about 5.5 kg CO_2 per kg N (Leach 1976) and as both fertilisation and legume rotations increase emissions of nitrous oxide (Prather et al. 1995).

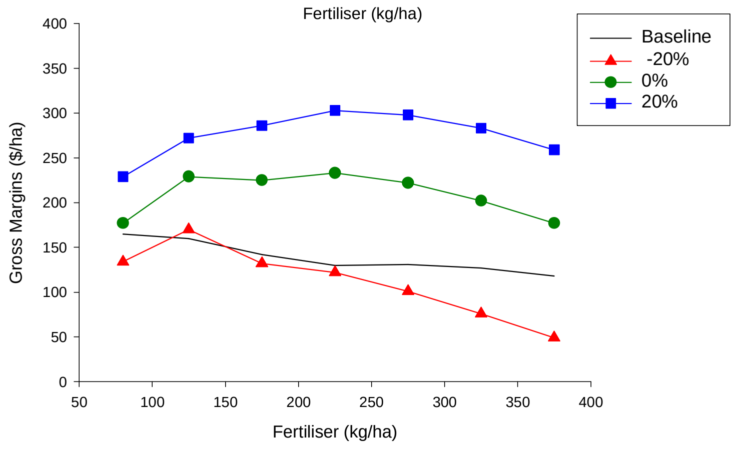

Figure 2.3: Gross Margins ($/ha) for wheat in Wongan Hills (WA) under different fertiliser application rates (kg N/ha) for a 4°C temperature increase scenario with different rainfall scenarios (-20%, no change and +20%). Note, all climate change scenarios are run assuming 700ppm CO_2.

Knowledge gaps and priorities

The sections above have detailed a large range of potential adaptation options. Some of these are largely new activities that may need to be implemented specifically in relation to climate and atmospheric changes (e.g. breeding to maximise grain protein in the face of higher levels of CO_2). However, many of these options are currently being implemented to greater or lesser degrees as part of managing for climate variability, market vagaries, extant pest, disease and weed problems or the rundown of natural resources. Climate change is likely to raise the importance of these adaptations and require more widespread and rigorous implementation, often based on ongoing research, development and extension (RD&E). In this context, even though strictly some of these adaptations do not qualify as knowledge gaps (as there is some related prior work), they are frequently likely to be key adaptations, thus remaining a priority.

One key knowledge gap that does not fit well into the format of the table below is how to implement adaptation across the value chain of the cropping industries. This will likely involve multiple interacting adaptations, dealing with technical, managerial, structural and policy aspects and interacting with a large range of other stressors, opportunities and barriers. The analysis of this needs to be considered in an even broader framework that uses participatory approaches to translate climate scenarios to biophysical impacts on crops and cropping systems to enterprise level adaptation options to farm financial impacts to regional and value-chain economic and social impacts (such as via livelihoods analysis) and then through to policy options. Integration and adaptive learning are critical and could occur through social and analytical links back to the enterprise scale.

Table 2.3: Summary of climate change adaptation options for the grain industry indicating whether the option 1) has already been assessed or is a remaining knowledge gap, 2) is highly feasible, 3) would be feasible / effective immediately, or 4) should be a high priority for research, assessment and implementation in developing adaptation strategies.

All adaptations	Options already assessed	Options with high feasibility	Immediacy	Priority activities
Adaptation to climate change – policy level				
Develop linkages to existing government policies and initiatives e.g. GGAP, Greenhouse challenge, salinity, water quality, rural restructuring	X	✓	✓	✓
Ensure communication of broader climate change information	✓	✓	✓	✓
Maintenance of effective climate data distribution and analysis systems	✓	✓	✓	✓
Modification of existing Federal and State Drought policies to encourage adaptation	X	X	✓	X
Continue training to improve self-reliance and to provide knowledge base for adapting	✓	✓	✓	✓
Policy settings that encourage development of effective water-trading systems that allow for climate variability and support development of related information networks	✓	✓	✓	✓
Public sector support for a vigorous agricultural research and breeding effort with access to global gene pools	✓	✓	✓	✓
Maintain R&D capacity, undertake further adaptation studies which include costs/benefits and streamline rapid R&D responses	✓	✓	✓	✓
Develop further crop systems modelling capabilities such as APSIM and quantitative approaches to risk management	✓	✓	✓	✓
Encourage appropriate industry structures to enable flexibility	X	X	✓	X
Encourage diversification of farm enterprises	✓	X	✓	X
Ensure support during transition periods caused by climate change and assist new industry establishment	X	✓	X	X
Altering transport and market infrastructure to support altered production regimes caused by climate change	X	✓	X	X
Encourage financial institutions to be responsive to	X	✓	X	X

changing industry needs				
Continuing commitment from all levels of government for pest, disease and weed control including border protection	✓	✓	✓	✓
Introduction of climate change adaptation into Environmental Management Systems	X	✓	✓	✓
Adaptation to climate change – crop and farm management				
Development of participatory research approaches to assist pro-active decision making on-farm and across the value chain	✓	✓	✓	✓
Develop further risk amelioration approaches (e.g. zero tillage and other minimum disturbance techniques, retaining residue, extending fallows, row spacing, planting density, staggering planting times, erosion control infrastructure)	✓	✓	✓	✓
Develop further controlled traffic approaches – even all-weather traffic	✓	✓	✓	✓
Research and revise soil fertility management (fertilizer application, type and timing, increase legume phase in rotations) on an ongoing basis	✓	✓	✓	✓
Alter planting rules to be more opportunistic depending on environmental condition (e.g. soil moisture), climate (e.g. frost risk) and markets	✓	✓	✓	✓
Expand routine record keeping of weather, production, degradation, pest and diseases, weed invasion	X	✓	✓	✓
Tools and extension to enable farmers to access climate data and interpret the data in relation to their crop records and analyse alternative management options (e.g. Yield Prophet).	✓	✓	✓	✓
Adaptation to climate change – climate information and use				
Improve dynamic climate modelling tailored towards decision making in agriculture	X	X	✓	X
Incorporate seasonal forecasts and climate change into farm enterprise plans so as to be able to readily adapt	X	✓	✓	✓
Maximise utility of forecasts by RD&E on combining them with on-ground measurements (i.e. soil moisture, nitrogen), market information and systems modelling.	✓	✓	✓	✓
Warnings prior to planting of likelihood of very hot days and high erosion potential	X	✓	✓	✓
Adaptation to climate change – water resource issues				
Further improvements in water distribution systems (to reduce leakage and evaporation), irrigation practices such as water application methods, irrigation scheduling and moisture monitoring to	✓	✓	✓	✓

increase efficiency of use				
Maintain access rights to water	✓	?	✓	?
Develop water trading system (and associated information base) that can help buffer increased variability	X	✓	✓	✓
Maximise water capture and storage on-farm – needs R&D and policy support	✓	✓	✓	✓
Adaptation to climate change – managing pests, disease and weeds				
Improve pest predictive tools and indicators	✓	✓	✓	✓
Improve quantitative modeling of individual pests to identify most appropriate time to introduce controls	✓	X	X	X
Further development of Area-wide Management operations	✓	X	✓	?
Further development of Integrated Pest Management	✓	✓	✓	✓
Improved monitoring and responses to emerging pest, disease and weed issues	✓	X	✓	X
Adaptation to climate change – crop breeding				
Selection of varieties with appropriate thermal time and vernalisation requirements, heat shock resistance, drought tolerance (i.e. Staygreen), high protein levels, resistance to new pest and diseases and perhaps that set flowers in hot/windy conditions	✓	✓	✓	✓
Ongoing evaluation of cultivar/management/climate relationships	✓	✓	✓	✓
Adaptation to climate change – landuse				
Potential for cotton, summer-growing grains and pulses further south	X	✓	X	X
Movement to more livestock in the enterprise mix	X	✓	X	X

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3: COTTON

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Key Messages:

- Less availability of water resources resulting from climate change will increase competition for these resources between irrigated cotton production and other cops and environmental uses which emphasises the need for continual improvement in whole farm and crop water use efficiencies.
- There will be a need to maintain and increase cotton profitability through practices that increase in both yield and fibre quality, whilst improving resource use (especially water and nitrogen use).
- Regional specific effects will need to be assessed thoroughly as the predominant cotton production regions span from southern NSW to north Queensland. This is necessary so that cotton growers can assess likely impacts at their business level. Research into the development of responsible and sustainable cotton systems for northern Australia where water supply is more assured is also needed.
- Research into integrated affects of climate change (temperature, CO_2, and water stress) on cotton growth, yield and quality need further analysis. Including the development of varieties tolerant to abiotic stress (especially heat and water deficits). Consideration or allowances in these studies of adaptation of both cotton cultivars and insect pests that will have been selected in rising CO_2 environments is also needed.
- Cotton is adapted to hot climates. With the current geographical spread of Australia's cotton breeding program along with new biotechnology tools and other plant and crop physiological research identifying and assessing adaptation traits, new varieties with improved water use efficiency and heat tolerance will be selected that are better suited to climate variability and change.
- Maintain R&D capacity, undertake further adaptation studies which include costs/benefits and develop focused and streamlined rapid R&D responses.

Introduction

Much of the material provided in this report on cotton was taken from a scoping document prepared for the Australian Cotton Industry as part of the Climate Change in Cotton Communities project funded by the Australian Greenhouse Office and the Cotton Catchment Communities Cooperative Research Centre (McRae *et al.* 2007).

Cotton is a natural fibre produced by the cotton plant, a leafy, green shrub and a member of the Hibiscus family. Although cotton is a perennial shrub that grows naturally to 3.5 metres, commercially it is grown as an annual crop. Australia's cotton growing season usually starts in September and October with planting and finishes in March to April with picking.

Everyday, clothing made from cotton fibre and products made from cotton seed oil are used. Cotton is the most widely produced natural fibre in the world and represents about 46 per cent of the global textile market. By contrast, wool accounts for 3 per cent, synthetics 51 per cent and other fibres like silk, hemp and mohair make up a very small proportion.

Cotton seed is a by-product of the more valuable cotton fibre, and makes up about 15 per cent of the total financial returns to farmers. For every 227 kilogram bale of cotton lint, about 300 kilograms of cotton seed is produced. Cotton seed is a valued raw material for food oils for human consumption and high protein feed for livestock. Cottonseed oil is one of the world's most popular vegetable oils.

The Australian Cotton Industry

Currently seventy per cent of Australia's cotton is grown in New South Wales (the Macquarie Valley, the Namoi Valley, the Gwydir Valley, Bourke, Hillston, Hay and Menindee districts) with the remainder grown in Queensland (the Macintyre Valley, Darling Downs, St George, Theodore, Biloela and Emerald regions) (Figure 1).

Depending on water availability about 400,000 hectares of irrigated cotton is grown in Australia. The area of dryland or rain grown cotton varies considerably from year to year depending on commodity prices, soil moisture levels and rain. The area of dry land crop can vary from 5000 to 120,000 hectares (Figure 2).

In an effort to expand the cotton growing regions and address some of the challenges raised by our variable climate, cotton growing has been trialled in northern Australia (including the Ord River Irrigation Area – Kununurra, and the Burdekin River Irrigation Area in north Queensland).

Broadly the regions could be described as:

1. Northern NSW (Namoi Valley, Gwydir Valley, Macquarie Valley, Bourke);
2. Southern NSW (Hillston, Hay and Menindee districts);
3. South Queensland (Macintyre Valley, Darling Downs, St George); and
4. Central Queensland (Theodore, Biloela and Emerald regions);
5. Northern Australia (Ord River and Burdekin Irrigation Areas).

Most Australian cotton farms are owned and operated by family farmers, are typically between 500 to 2000 hectares, are highly mechanised, capital intensive, technologically sophisticated and require high levels of management expertise. About 80 per cent of cotton farms are irrigated and as part of the enterprise mix generally grow other crops such as wheat and sorghum and/or graze sheep and cattle.

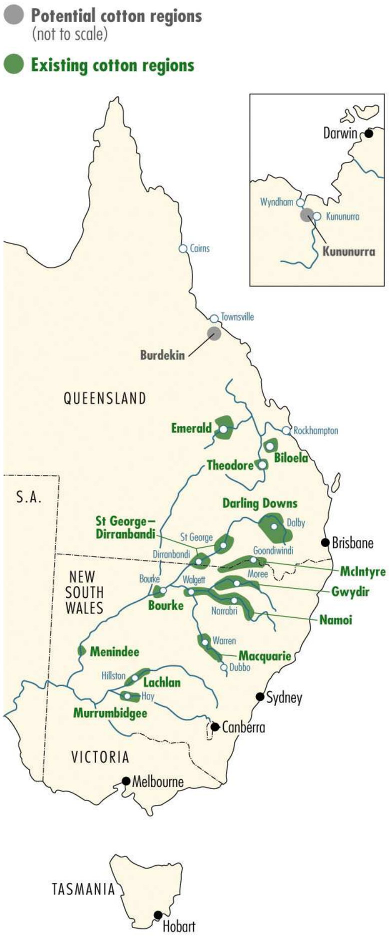

Figure 3.1: Australian cotton growing regions (Cotton Catchment Communities CRC)

Industry productivity

On a global scale Australia is a relatively small producer growing about 3 per cent of the world's cotton. Similar to other agricultural commodities grown in Australia, the Australian cotton industry is a large exporter. As of 2007 the largest cotton producers are the China, India, USA, Pakistan, Brazil, Uzbekistan and Turkey. Major importers of Australian cotton are Indonesia, Japan, China, Thailand and South Korea. Australia's reputation for producing high quality cotton means it is competitive in the international marketplace.

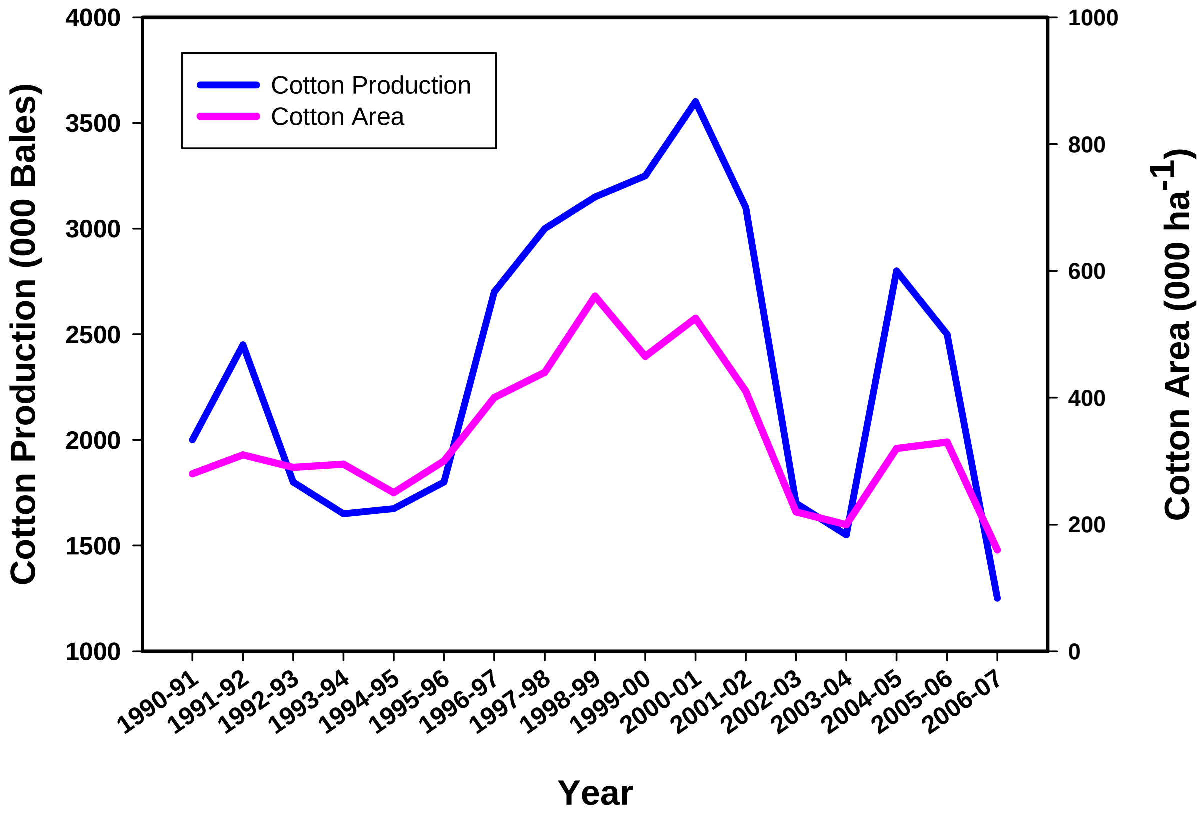

Figure 3.2: Area and overall production (bales) of the Australian cotton industry (source ABARE and RCMAC).

Since 1960, lint yields have increased at about 22 kilograms of lint per hectare per year. Australian average yields are now the highest of any major cotton producing country in the world and lint yields have continued to edge upwards from 1200 kg/ha in the 1970s, through 1400 kg/ha in the 1980s to 1600 kg/ha in the 1990s and are now above 1800 kg/ha. The adoption of research and development by Australian cotton growers has under-pinned these significant increases in production. According to International Cotton Advisory Committee forecasts, the average global yield during 2006/07 was expected to be 716 kg/ha which is well below Australian productivity levels.

The gross value of cotton produced in Australia has increased rapidly since 1985, with the exception of the drought years 1986, 1992 to 1994, and 2003/2004. The gross value of production peaked at $1.9 billion in 2000/2001 and was $1.2 billion in 2004/2005 and $1.1 billion in 2005/06 making the industry important not only for the economy in cotton growing communities but also for Australian community as a whole (http://www.cottonaustralia.com.au/). Drought conditions still plague the industry's access to water resources and continue to restrict cotton production (Figure 2).

Climate Change Impacts

Projections of Climate change Impacting Cotton Production

Key findings of the CSIRO (2007) climate change regional projections for Australia relevant for cotton production in Australia are:

Temperature

Key findings of the CSIRO 2007 climate change regional temperature projections for Australia include:

- The best estimate of annual warming over Australia by 2030 relative to 1990 is about 1.0ºC for the mid-range emissions.
- Warming is expected to be higher inland
- The pattern varies little seasonally, although warming is less in winter in the south. The range of uncertainty due to differences between models is about 0.6ºC to 1.5ºC for most of Australia, with the probability of the warming exceeding 1ºC by 2030 being 10-20% for coastal areas, and more than 50% for inland regions.
- An increase in the average number of extreme hot days and decrease in the average number of extreme cold days and frosts

Simply, this means a higher incidence and increased severity of heatwaves and a decline in the number of very cold nights. These changes have the potential to provide both opportunities and threats to the Australian cotton industry.

Rainfall

- Climate model results for rainfall change show decreases and increases for many locations.
- Where at least two-thirds of the spread of model results are less than zero, decreasing rainfall is considered 'likely'. Decreases in rainfall are likely in southern areas in the annual average and in winter, and in southern and eastern areas in spring. Otherwise the models do not give a likely direction of rainfall change, although model ranges show a tendency to decrease in most cases. In no region or season do models suggest a 'likely' increase in rainfall.
- For 2030, best estimates of annual rainfall change indicate little change in the far north and decreases of 2% to 5% elsewhere. Decreases of around 5% prevail in winter and spring, particularly in the south-west where they reach 10%. In summer and autumn, decreases are smaller and there are slight increases in New South Wales in summer.
- The range of rainfall change in 2030, allowing for differences between models, is large. Annually averaged, it is around -10% to +5% in northern areas and -10% to little change in southern areas. Winter and spring changes range from -10% to little change in southern areas of the south-east of the continent, -15% to little change in the south-west, and -15% to +5% in eastern areas. In summer and autumn, the range is typically -15% to +10%. There is a 20% to 30% chance of a simulated annual rainfall decrease of at least 10% in western and central areas, whereas the probability of a simulated increase of at least 10% is very low. Decadal-scale natural variability in rainfall is comparable in magnitude to these projected changes and may therefore mask, or significantly enhance, the greenhouse-induced changes.
- Models also show an increase in daily rainfall intensity (rain per rainy day) and in the number of dry days.
- Extreme daily rainfall tends to increase in many areas but not in the south in winter and spring when there is a strong decrease in mean rainfall.

Evaporation and Moisture balance

- A tendency towards an increase in potential evaporation of 0 to 8% per degree of warming throughout most of Australia with the larger tendency where there is a corresponding decrease in rainfall

- A tendency towards a decrease in the annual water balance throughout most of Australia of 40 to 120 mm per degree of warming
- This represents a decrease of 15 to 160 mm by 2030 and 40 to 500 mm by 2070 with the largest impact in spring

Even if rainfall remains consistent with long term averages, the rise in overall temperatures and potential decreases in water balance indicates greater moisture stress throughout Australia. Therefore water use efficiency, access to water and soil water management will remain dominate issues into the future.

Impact of Climate Change on Cotton Production

Cotton (*Gossypium hiristum* L.) is a perennial plant with an indeterminate growth habit. Wild ancestors of cotton are found in arid regions often with high temperatures and are naturally adapted to surviving long periods of dry weather. Modern cultivars have inherited these attributes, making the cotton crop well adapted to intermittent water supply that occurs with rain-fed (dryland) and irrigated production (Hearn, 1990). Compared with other field crops however, its growth and development is complex. Vegetative and reproductive growth occur simultaneously making interpretation of the crop's response to climate and management sometimes difficult.

Climate change impacts for cotton growth and development that influence yield and fibre quality will most likely be a result of the net effects of:

1. increases in (Carbon Dioxide) CO_2 concentration;
2. reduced water availability and increased atmospheric evaporative demand as a result of lower rainfall and relative humidity; and
3. increases in temperature.

These effects are discussed in more detail below.

Increases in CO_2

Two sources of research are currently available that discuss the impact of CO_2 on cotton's growth and development. Both studies were in controlled conditions in the USA.

The first block of research summarised by Reddy et al. (1996) discusses impacts of CO_2 increase on cotton in growth chambers. This work showed that doubling CO_2 concentrations in the atmosphere increased photosynthesis by about 40% which led to increased growth and yield in well watered environments. This work also showed that increasing CO_2 increased water use; however, the efficiency of water use was improved. From their studies they postulated that increased growth and yield would occur with higher CO_2 concentrations even in dry or nutrient deficient situations. Using this work we could assume that with an increases in CO_2 to levels predicted for 2020 (406 to 415 ppm) and 2050 (473 to 555 ppm) photosynthesis would increase by approximately 23 and 29% respectively.

In other work by Pinter et al. (1994) on field grown cotton, they explored increases in CO_2 using free air CO_2 enrichment (FACE) facilities. They found that radiation use efficiency (dry matter per unit of intercepted radiation) was improved on average from 1.56 to 1.97 g MJ^{-1} resulting in increased biomass when CO_2 was increased to 550 ppm. In addition they also investigated the impact of CO_2 elevation with different irrigation regimes. They found that regardless of irrigation treatment (wet or dry) radiation use efficiency was increased in CO_2 elevated treatments. This suggested that a rise in atmospheric CO_2 concentrations may partially compensate for plant stress caused by water shortages. As a consequence lint yield on average was increased by 43% and was attributed to increased early leaf area and a longer flowering period (Mauney *et al.* 1994).

Recent research on cotton into elevated CO_2 (doubling of current ambient) has also shown that it can affect leaf chemistry reducing concentrations of the Bt toxin expressed in transgenic cotton cultivars used to control *Helicoverpa* spp (Wu et al. 2007) by up to 3.1%. While this research suggests changes in plant-herbivore interactions these changes have not necessarily translated into reductions in performance of the transgenic cultivars (Chen et al. 2007; Wu et al. 2006). There is some evidence to suggest that *Helicoverpa* spp. are adversely affected by feeding on cotton subjected to elevated CO_2 as there lifespan is increased however, there pupal weight, survival rate, fecundity, frass output, relative mean growth rates, and the efficiency of conversion of ingested and digested food is decreased. All these factors lead to adverse effects on *Helicoverpa* spp. population size and dynamics.

Detailed research that investigates a greater range of water stress and higher temperature scenarios (especially in Australian climatic conditions) to properly assess the impact that elevated CO_2 on cotton growth and insect pests, and the translation of these changes into yield and quality are needed. Consideration or allowances in these studies of adaptation of both cotton cultivars and insect pests that will have been selected in rising CO_2 environments is also needed.

Reduced Water Availability and Higher Evaporative Demand

Undoubtedly less water for irrigation will mean reduced cotton yield unless improvements in farm and agronomic water use efficiencies can improve. Water stress in cotton restricts both vegetative and fruit growth. Cotton's response to stress varies on the stage of growth, the degree of stress, and the length of time imposed. Research in Australia has shown that to optimise yield, cotton crops generally require on average enough water to allow 700 mm of evapotranspiration (transpiration plus soil evaporation) (Tennakoon and Milroy 2003).

Recent research in cotton has shown that regardless of the water availability in the soil there is an increase in plant stress associated with higher evaporative demands (Neilsen 2006). Higher evaporative demand in well watered crops has the potential to increase transpiration and soil evaporation lowering water use efficiency. In situations where water is limited and there is high evaporative demand, crops will struggle to transpire enough to keep the canopies cool. Leaf temperatures are then increased to a point where photosynthesis and growth are impaired (Hearn and Constable, 1984). Research is currently being undertaken to quantify the effects of relative humidity on cotton growth on soils with different water holding capacities.

Water availability and changes in relative humidity will affect all cotton production regions.

Increase in Temperature

Temperature has two main influences on cotton growth and development. Firstly it determines rates of morphological development and crop growth (eg. node development, rate of fruit production, photosynthesis and respiration) (Hearn and Constable, 1984). Secondly, it also helps determine the start and end of a growing season (eg. timing of frosts).

Consequently climate change raising temperatures may: increase average daily temperatures warming both the start and end of cotton seasons allowing for longer and better cotton growth (a positive effect); increase average temperatures during boll filling predisposing crops to high micronaire issues (a negative effect); and increase the number and severity of days with very high temperatures during the cotton season (negative effect). Both negative and positive effects are discussed below:

<u>Increase in frequency of very hot days</u>

Many areas in which cotton is grown around the world and in Australia already experience extremely high temperatures during the growing season (Figure 3), particularly during flowering and boll development. Climate change may increase the frequency of these high temperatures. Cotton plants maintain optimum growing temperatures by opening stomates in the leaves, allowing water to pass out and evaporate, thus cooling leaves (transpiration).

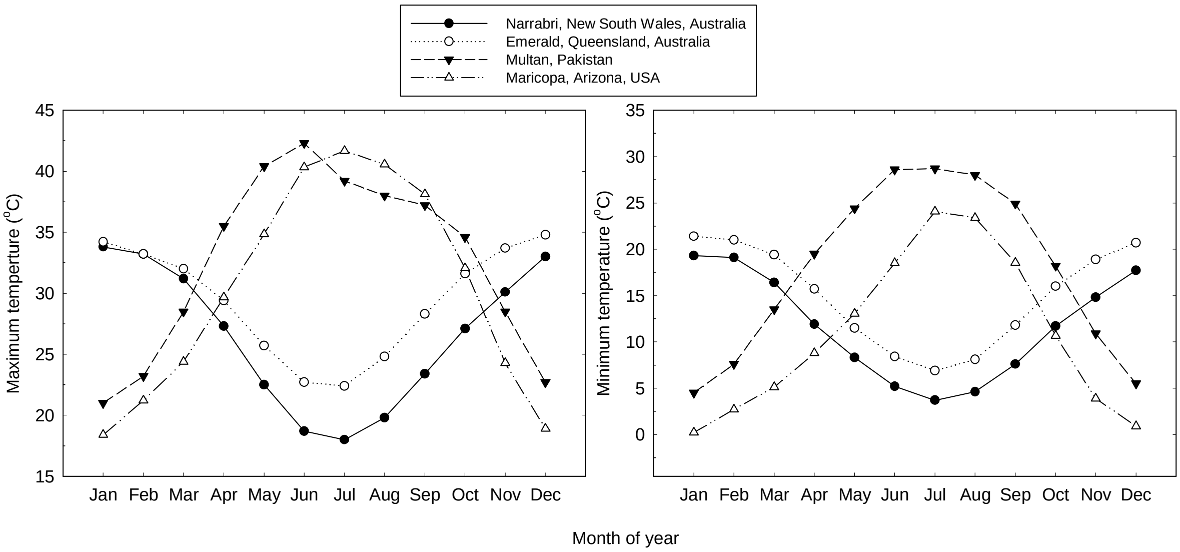

Figure 3.3: Comparison of monthly average maximum and minimum temperatures for Narrabri and Emerald (Australia, Source Bureau of Meteorology) and other hot cotton production areas Maricopa, Arizona (USA) and Multan (Pakistan) (Source www.weatherbase.com). Yield potential is significantly less in Maricopa and Multan as a result of the hot temperatures.

The impacts of high temperature have been reviewed by Hearn and Constable (1984). Excessively high temperatures (greater than 35ºC) during the day can decrease photosynthesis while warm nights (above 25ºC) mean that leaf temperature remains high, and respiration remains high, consuming stored assimilates. Maintenance respiration approximately doubles for every 10 ºC rise in temperature. Both situations reduce the amount of assimilates available for growth, and in turn reduce yield by: causing increases in square and boll shedding; and reducing seed number per boll. Loss of fruit may cause the crop to grow excessively vegetatively (rank) following the period of heat stress.

In addition to reductions in assimilates available for growth, heat stress can also directly damage cotton plant tissue. During the day very high relative humidity (which restricts evaporative cooling) in combination with clear skies can also increase tissue temperature to approach or exceed air temperature. Two known consequences of direct tissue damage from severe heat stress are:

- Parrot Beaked Bolls – High temperatures reduce the viability of the pollen at flowering. This reduces boll size and can reduce yield. The result is small bolls with uneven seed numbers between the locks caused by poor pollination /seed set particularly in one lock. There are no known studies to show if the plant compensates for parrot beak bolls by having other normal bolls grow bigger.

- Boll Freeze, Cavitation or Boll Dangle – Occurs when young bolls die before the abscission layer forms. Again this loss of fruit may cause the crop to grow excessively vegetatively (rank) following these symptoms.

Large increases in temperature also reduce the interval between flowering and boll opening, shortening the time to maturity and reducing yield. This may increase final micronaire by limiting the number of late set bolls that can have lower micronaire. Fibre length can also affected by sustained periods of high temperatures as the time required for fibre elongation is reduced, not allowing for genetic potential for fibre length to be reached. Stockton and Walhood (1960) found that as boll temperatures increased above 32 ºC fibre length was reduced.

The consequences of hot conditions for yield and quality are exaggerated if water stress also occurs during these periods. These issues will be important for all cotton producing regions.

<u>Warming the start and end of cotton seasons</u>

Increased average temperatures especially at the start and end of cotton season can have positive effects on growth, development and ultimately yield.

Low temperatures after sowing increase the time to emergence and reduce cotton seedling vigour often leading to poor establishment, poor early growth and increased risk of seedling diseases (Constable and Shaw 1988). A key indicator used in the Australian cotton industry of the degree of very cold temperatures that contribute to the conditions mentioned above is the ‘cold shock’ concept. A cold shock is defined as when minimum daily temperatures are ≤ 11°C and each event extends the duration to flowering by 5.2 day degrees (Hearn and Constable 1984). In some cotton producing regions in Australia early in cotton growth the number of cold shocks can be as frequent as 40 (period 15th Sep. to 30 Nov.). Climate change has the potential to raise minimum temperatures and significantly reduce the number of cold shocks.

Cotton is a perennial crop; warmer temperatures at the start and the end of cotton seasons will increase the length of time cotton has to grow and produce yield, provided adequate water and crop nutrition are available. For every extra week that the growth period (time between sowing and maturity) may be allowed to be extended through warmer temperatures it has the potential to increase lint yield by 68 and 136 kg ha^{-1} (Bange and Milroy 2004).

Extending cotton season has the potential to benefit the northern and southern NSW and southern Queensland cotton producing regions especially the eastern boundaries of these areas where cooler conditions prevail. It also provides growers with greater flexibility with sowing dates at the start of the season.

Warmer temperatures during boll filling

A key factor effecting micronaire (a fibre quality trait) is the temperature during boll filling. Micronaire is a measure of fibre fineness and maturity. Fibre fineness is determined primarily at fibre initiation on a seed. Finer fibres mean that there are more fibres in the cross section of a yarn when it is spun and thus the yarn is stronger. Fibre maturity is the proportion of fibre cross section occupied by cellulose and is influenced by variations in photosynthesis affecting assimilate supply and demand for resources by the developing bolls. The degree of fibre maturity impacts dye absorbency and retention. As photosynthesis increases with temperature in the absence of water stress, more resources are available to mature the fibres thus increasing micronaire. Situations where seasons are warmer more often during boll filling predispose crops to situations where high micronaire will be more likely to occur.

With the exception of southern NSW and some parts of northern NSW which have shorter growing seasons which often predispose them to lower micronaire, the issues of higher and less desirable micronaire will be an issue for all other production regions. This may also benefit cotton production in northern Australia (especially the ORIA) as there are also issues of low micronaire when cotton is grown in the dry season from cooler temperatures.

Adaptation Options

Current Options for Dealing with Climate Variability

The wide geographic spread of the industry means that management practices are different in cotton producing regions in response to their various climates. Specific cotton crop management options for dealing with issues relating to climate variability are summarised below:

Variety Selection

Variety choice is a strong component of realising both target yield and fibre quality levels on farm. A delicate balance needs to be resolved between yield, fibre quality, price and other important considerations such as disease resistance, and insect and herbicide resistance. To meet this need Australian cotton breeding programs are already aimed at developing cotton varieties well suited to the environmental and climatic conditions experienced throughout all the cotton production regions (hot and cool), and therefore give growers options for selecting varieties suitable to their conditions.

Varieties developed by CSIRO dominate the Australian cotton market. CSIRO's investment in research and plant breeding has already developed varieties with known high heat tolerance (Constable *et al.* 2001), which will help to accommodate climate change especially for regions in Southern Queensland and Northern NSW. In addition to these breeding efforts accounting for regional climatic diversity there is also specific breeding program in place for rain-fed cotton production. This means that there are already varieties that are better adapted to less than fully irrigated and stressed conditions.

With the assistance of new biotechnology tools as well as the measurement of yield performance under varying environmental conditions and other physiological measurements assessing adaptation traits, cotton breeding efforts are already focused on identifying genes and cotton germplasm to improve water use efficiency and heat tolerance to better adapt to climate variability and change. As cotton is already grown in hotter climates than currently experienced in Australia (Figure 3), there is significant potential for accessing germplasm that may offer improved heat tolerance.

Planting time variation

Changing planting time offers Australian growers a 'systems solution' that can provide benefits both in terms of: maintaining yield; improving fibre quality; reducing the risk of adverse effects of high temperatures; and reducing the incidence of seedling diseases early in the season. Recent research by Bange *et al*. (2007) with the introduction of transgenic cultivars (with improved insect protection that lead to crops with higher fruit retention) have shown that in the Northern NSW region delaying sowing time could maintain yield and improve fibre quality (both in terms of fibre length and micronaire). In a changing climate with the introduction of new varieties there will need to be ongoing reassessment of planting time as a management option in the different cotton production regions. Current research is assessing the water and nitrogen use efficiencies of different planting dates.

Irrigation management

Most cotton in Australia is fully or partially irrigated which serves to reduce climate variability associated with rainfall. However, recent drought conditions coupled with reductions in water allocation across all major cotton production regions has placed significant emphasis on managing water resources more efficiently. Practices that Australian cotton growers have adopted with an aim to improve the water use efficiency include:

- Implementation of systems that monitor and assess whole farm water use efficiency to identify parts of the system which are inefficient. Growers consistently adopt practices to improve water storages, and reduce transmission and application losses.
- Use of alternative irrigation systems such as lateral move or drip irrigation systems.
- Use of technologies to monitor weather (automatic weather stations) and crop soil water use (capacitance probes, neutron moisture meters) to better schedule irrigations.
- Improving soil management by adopting reduced tillage practices to minimise compaction which improves soil structure and increases the rooting zone.
- Adoption of management practices in limited water situations by:
    - Reducing risk of crop failure by modifying the amount of the area of cotton grown before the season begins.
    - Choosing varieties suited to production regions which also have inherently higher fibre length to reduce the risk of incurring financial penalties for short fibre length.
    - Avoiding excess nitrogen so that vegetative growth is discouraged. This also has the benefits of reducing nitrogen dioxide emissions (greenhouse gas).
    - Avoiding stress during the flowering period.

Recent research and advancements in irrigation and water management in the Australian cotton industry has been summarised by Roth (2007).

Rain-fed Cotton Systems

Rain-fed cotton production can be a significant proportion (as high as 15% of total production area) of the Australian Cotton Industry especially in those years where prices for cotton are acceptable and there is a forecast for reasonable rainfall Bange *et al*. 2005). One of the management techniques that rain-fed cotton growers have is to modify row configuration. Configurations that have entire rows missing from the sowing configuration are often referred to as 'skip row'. Skip configurations are used to: increase the amount of soil water available for the crop, which can influence the potential lint yield; reduce the level of variability or risk associated with production associated with climate variability; enhance fibre quality; and reduce input costs (Bange *et al.* 2005).

Manipulating Crop Maturity

Crop maturity can be manipulated by choice of cultivar, insect management, nutrition, or late season irrigation management. Early crop maturity may allow growers to pick the crop in a timely manner to avoid quality down grades and perhaps save on water or late season insect protection. However, this needs to be balanced against the fact that in the Australian environment reduces lint yield by 68 and 136 kg ha^{-1} per week (Bange and Milroy 2004). Reducing the time to maturity and managing a crop to achieve targeted economic yield threshold is an option in those climates that have limited water availability.

Crop Nutrition

Monitoring soil fertility and crop nutrient uptake has become commonplace within the Australian cotton industry, as growers realise the importance of avoiding nutrient deficiency and the economics and environmental concerns of excess fertiliser use. Currently, the NutriLOGIC decision support system provides information for determining the appropriate rates for N fertiliser use and the need other nutrients based on crop stage (utilising climate information) and performance.

While cotton yields have increased steadily over the past decade, so have N fertiliser application rates in most regions. Also, use of P and K fertilisers has increased. The cotton industry promotes effective use of fertilisers in the Best Management Program largely to minimise the risk of environmental damage from nutrient leaching and greenhouse gas emissions. Crop nutrition research is however reporting a wide range of nutrient use-efficiencies, indicating scope for improvement in some circumstances (Rochester *et al.* 2006).

Legume rotation crops are grown so cotton growers can reduce N fertiliser use, improve P and K nutrition of following cotton, and improve overall soil quality (Rochester and Peoples 2005; Rochester 2004).

Nutrient removal escalates as yield increases. Hence, there is increased grower interest to maintain high soil fertility by applying equivalent amounts of macronutrients nitrogen (N), phosphorus (P) and potassium (K) to those removed in seed cotton (Rochester 2007). By applying these nutrients, growers can arrest soil fertility decline and delay or avoid the onset of nutrient deficiencies, even though there may be no lint yield response to P or K application. This constitutes a strategic change in nutrient management, instead of applying fertilisers where there was an economic response to nutrient application. Growers are combining nutrient removal information with more traditional soil and tissue testing, so they can ensure soil fertility is maintained and crop nutrition improved.

Pest Management

One major production issue that these growers face each season is the protection of the crop against a range of insect and mite pests. Key invertibrate pests of Australian cotton include *Helicoverpa armigera* and *Helicoverpa punctigera*, spider mites (*Tetranychus urticae*), aphids (*Aphis gossypii*) and mirids (*Creontiades dilutus*). The insect pest and beneficial complex is broadly similar for all cotton growing regions (including northern Australia). To control these pests they have historically relied strongly on intervention with chemical pesticides, which remain a significant component of the cost of production (Fitt and Wilson 2000). In addition the use of chemical sprays gives rise to ecological problems from pesticide resistance in key pests, and environmental concerns about pesticide movement off-farm (Wilson et al. 2003; Fitt 2000).

The development of transgenic cotton with two Bt genes (Bollgard II) has reduced pesticide use for the control of major *Lepidopteran* pests (particularly *Helicoverpa* spp.) however, as the system is changing pests formerly suppressed by these sprays for *Helicoverpa* spp. are emerging as new challenges. The Australian industry is modifying IPM strategies to meet the challenges of emerging pests as well as maintaining viability of conventional and transgenic systems against pesticide resistance (Wilson *et al*. 2003).

Seasonal climate variability (especially in relation to variations in temperature and rainfall) influences the distribution and abundance of insect pests. Temperature directly affects insect, development, survival, number of generations, timing and the duration of diapause, while rainfall affects the growth of plant hosts leading to differences in distribution and abundance of insect pests.

In the past the industry has experienced extremely wet and very dry years and the pest issues associated with these climates. Wet and warm years have seen abundant winter and summer weed hosts contributing to pest build ups. Hot dry years when irrigation water is available are favourable for cotton growth and most likely have less insect pest build also contributing to improved yields. A particular issue encountered in warmer seasons is the increasing abundance of silver leaf whitefly (*Bemisia tabaci* B-Biotype) due to more generations developing in the warmer conditions. In a climate change scenario where southern regions may become warmer, whiteflies maybe become more of an issue.

One of the fundamental elements of an IPM approach adopted by the Australian industry is the regular and accurate monitoring of the numbers of pest and beneficial insects and the use of economic thresholds to guide decisions on pest management. In doing this growers are already responding accordingly and adapting to regional and seasonal variation.

Differences in weeds and crop diseases also occur across regions and seasons because of variation in rainfall and temperature. Australian cotton growers employ the use of transgenic cotton that allows over the top application of glyphosate for weed control to allow for rapid response to weed control along with integrated weed management. In the case of diseases cold wet conditions are favourable for Black root rot (*Thielaviopsis basicola*), Fusarium Wilt (*Fusarium oxysporum*) and Verticillium Wilt (*Verticillium dahliae*). When conditions are warm and moist Alternaria Leaf Spot (*Alternaria macrospore* and *Alternaria alternata* can be an issue. The industry employs an integrated disease management approach, and breeding efforts are heavily focussed on developing germplasm with in-built resistance.

Changes in climate will need to ensure industry monitoring strategies are in place to identify changes in the pest, weed and disease spectrums, especially those that prefer warmer climates. There is significant opportunity to further develop pest forecasting systems that can be used to predict the effects of climate change. As an example, a simulation model already used in the Australian cotton industry for *Helicoverpa* spp. is the HEAPS (HElicoverpa Armigera and Punctigera Simulation) model which has been used to assess movement of adult moths within a regional cropping system (Fitt et al 1995). HEAPS includes modules for spatial representation if the region, moth movement, oviposition, pest and crop development and pest mortality. Components of this technology have been available to industry via decision tools (Hearn and Bange 2002).

Regional Expansion

There is significant opportunity for cropping regions such as the Ord and Burdekin Irrigation Areas in northern Australia to produce cotton. Despite unsuccessful attempts at cotton production in northern Australia in the past, the introduction of transgenic cotton with in-built protection to *Helicoverpa* spp. as well as adopting cropping practices tailored specifically to these regions has meant cotton production may well be a viable alternative for cropping producers established in these regions. For the industry as a whole these regions have generated significant interest with the opportunity of more reliable water supply for production compared with existing cotton regions that have limitations to water supplies as a result of recurring droughts and reductions to allocations. An issue that may well be perpetuated with climate change.

For the Ord River Irrigation Area research has demonstrated that cotton can be grown sustainably when grown with transgenic insect protected cotton in the dry season. Management guidelines specific to this region have been developed (NORpak - Ord River Irrigation Area cotton management guidelines 2007). In the Burdekin Irrigation Area research is currently underway to develop a sustainable system with key challenges relating to climate variability. The challenges are low radiation and high humidity during cotton growth and ensuring integration with sugar cane cropping systems (Grundy and Yeates 2007).

Extension Material and Decision Tools

Guidelines for crop management practices specific to Australian cotton systems are delivered in through publications and decision support tools. These publications make specific reference to managing climate variability and are made available through the Cotton Catchment Communities website (http://www.cotton.crc.org.au/). Some significant publications include:

- WATERpak – provides technical information and practical advice to help cotton irrigators improve irrigation practices, minimise environmental impacts, and increase farm profits from cotton.
- NUTRIpak – a manual of cotton nutrition, designed to inform cotton growers and consultants of the importance of providing their crops with a sufficient supply of nutrients and improving their fertiliser management.
- FIBREpak introduction - contains information for managing fibre quality at every step, from pre-planting to processing.
- NORpak - Cotton production and management guidelines for the Ord River Irrigation Area (ORIA).
- IPM guidelines - guidelines designed to assist growers implement IPM strategies to suit their individual farming systems that account for the cotton growing season as well as other times of the year.

- WEEDpak - a guide for integrated management of weeds in cotton.
- Australian Dryland Cotton Production Guide – specific considerations for managing rain-fed cotton.
- Integrated Disease Management Guidelines for Australian Cotton - a tool to assist the management of diseases in cotton.

Decision support tools available to the Australian cotton industry that integrate knowledge of cotton management and climate that can be used to specifically deal with climate variability include:

- OZCOT cotton crop simulation model (CSIRO Plant Industry; Hearn 1994) is available to the Australian cotton industry for use in research assessing the impact of climate variability and management on yield on both irrigated and dryland cropping systems (Milroy et al. 2004). OZCOT is also the cotton module contained within APSIM model (Keating et al. 2003). Current research for OZCOT is focussed on the models ability to simulate high fruit retention transgenic cotton and enabling the model to predict fibre quality.
- HydroLOGIC - a stand alone software application to assist in the effective and timely application of irrigations for furrow irrigated cotton crops. It is able to provide information to help growers assess the consequences of different irrigation strategies on crop growth, yield and water use. Utilises climate databases and the OZCOT cotton crop simulation model.
- Cotton Day Degree Calculator – web application that utilises SILO patched point datasets that assess cotton crop development and compares with historical averages (http://tools.cotton.crc.org.au/Tools/Agronomy/SILODayDegCalc.htm).
- Crop Development Tool – web application that assists growers to monitor the performance of their crops in relation to potential growth based on prevailing climate. (http://tools.cotton.crc.org.au/CottonLOGIC/Cdt/).
- CottBASE – a standalone software application based on the Whopper Cropper software concept that is used to analyse pre-run simulations of the OZCOT cotton simulation model to assess the effect of climate variability on cotton irrigation practice.
- Cotton Greenhouse Gas Calculator – web application that estimates greenhouse gas emissions from use of nitrogen fertiliser and fuel consumption (http://www.isr.qut.edu.au/tools/index.jsp).
- NutriLOGIC – a web application that estimates fertiliser requirements of cotton based on soil and plant measurements and crop stage estimated from prevailing climate (http://tools.cotton.crc.org.au/CottonLOGIC/NutriLOGIC/).
- Helicoverpa Diapause Induction and Emergence Tool – a web application that predicts seasonal potential insect (*Helicoverpa* spp.) related issues based on the SILO patched point datasets (http://tools.cotton.crc.org.au/cl2/diapause/index.aspx). Will adjust predictions based on temperature.

Cotton growers in many instances grow other crops so they have access to knowledge and technology available to other cropping industries. In addition cotton growing is also serviced by agronomists and consultants that enhance access to specialised knowledge on cotton production (http://www.cottonconsultants.com.au/).

Adaptation Options for Dealing with Climate Change

Many of the potential adaptation responses available to the Australian cotton industry have production efficiency benefits regardless of the rate and nature of future climate change. Key industry production issues that will encompass climate change include:

- Improving nitrogen use efficiency of crops.
- Improving water use efficiency of the whole cotton farming system. Cotton growers are increasing seeing themselves as irrigated growers rather than just cotton growers to be more opportunistic for gains in water use.
- Improving management of climate variability (improving use of short, medium and long-term weather and climate forecasts, improving climate risk management including understanding and managing the trends and extremes regionally and globally for production and implications for our markets such as impact of potential global drying trends on our competitors).
- Plant breeding and farming systems to take advantage of increased temperatures, handle increased water stress, improve agronomic water use efficiency, and respond to elevated atmospheric CO_2.
- Avoiding resistance of pests (both insects and weeds) through appropriate integrated pest and weed management systems to maintain transgenic technologies.
- Capacity to forecast likely pest pressures.
- Auditing energy use in cotton farming systems including developing benchmarks and tools to assess and improve efficiency and being ready to exploit opportunities such as bio-diesel.
- Developing Best Management Practices for minimising the industry's greenhouse carbon footprint.

Given that there will be the no one solution for all of the challenges raised by climate change and variability the best adaptation strategy for any industry will be to develop more resilient systems. Early implementation of adaptation strategies particularly in regard to enhancing resilience, have the potential to significantly reduce the negative impacts of climate change (Howden *et al.* 2003).

Costs and Benefits

No explicit investigation of the benefits of implementing adaptation practices for climate change has been conducted for the Australian cotton industry. However, a recent report commissioned by the Cotton Research and Development Corporation and the Cotton Catchment Communities CRC by Boyce Chartered Accountants (2007) showed average expenses for cotton production have risen significantly as a result of increases in costs of chemical insecticides, fertiliser, fuel and oil, and water charges and purchases, thus reducing profitability. This only emphasises the importance of those adaptation strategies identified and mentioned previously.

There is a genuine need for information that helps identify the value (including economic, environmental and social) and the degree of change required of strategies that help meet issues of changing climate, resource limitations (such as water), along with rising production costs to ensure cotton's viability. This analysis needs to be conducted as soon as possible so that industry can appropriately focus it's investment on the most successful adaptation strategies.

Knowledge Gaps and Priorities

As part of the Climate Change in Cotton Communities project funded by the Australian Greenhouse Office and the Cotton Catchment Communities CRC, climate change workshops were run at Narrabri, Dalby, St George, Goondiwindi and Emerald in 2007. Some common themes that highlighted knowledge gaps, priorities and opportunities for further discussion within the cotton industry were developed. A sample of feedback from workshop participants covered by those themes included:

Crop Management/Agronomy

- Management is the key – always has been always will be
- Opportunities to take advantage of increased temperatures especially at the start and end of the growing season
- Better manage current system; row configurations, irrigation strategies, improve water storage and infrastructure
- Improve on-farm water use efficiency – aim to increase quantity and quality of yield over smaller area
- Use soil moisture tools and better scheduling of irrigation.
- Early maturing of crops using less water because of the shorter growing season. Opportunity to grow more crops in the rotation
- Plant breeding /transgenic development provides opportunities

Cotton Farming Systems

- Profitability in the short term is worrying growers more than climate change in the long term at the moment.
- Develop adaptable farming systems – already exists – manage for change as it occurs
- Designing a profitable and sustainable farm business – diversification and grow other crops.
- Educate about other suitable crops and drought tolerant varieties
- Diversify into other crops and livestock.
- Struggling with limited financial and time resources – solutions need to be realistic and profitable
- Develop a clear assessment of present impacts at the business level and what are the changes that can be made

Industry

- Water availability (access, government regulations) will be a challenge
- Industry expansion or relocation from traditional cotton growing regions raises a number of challenges - the expansion south may simply be a result of growers taking advantage of the recent window of warm weather and good prices and is into an area where there is already strong competition for water; while there may be more available water any further expansion into northern Australia will have pest and disease issues to overcome
- The industry is already dealing with climate change now
- Address community resilience - think globally and act locally - focus on the local scale
- Industries will respond at different rates
- Legitimate adaptation strategy is to exit industry
- Continue to build adaptive capacity and industry strengths
- Identify false hopes and promises like the shift to north Queensland – while it may provide increased access to water it raises different challenges with soil types and pest and weeds issues - so focus more on building industry resilience and less on industry relocation
- External pressures are overwhelming at times
- Link communities to the catchments as well as industry

Research

- Greater understanding on links to water availability and river flows is highest priority need
- Need more research on the impacts on quality (length particularly) and yield
- Need more research on the likely impacts of increased CO_2
- Utilise information currently available and don’t fund duplicate research.
- Need downscaled information - current broad (especially with rainfall) information little use at all
- Accept temperature projections but what about decadal wetter and drier patterns - it’s hard to believe that average rainfall is going to decrease in a straight line in Queensland and NSW

There is already significant investment in research that has specific aims to improve resource efficiency, and raise cotton yields and fibre quality. Recently the Cotton Catchment Communities CRC have instigated a research program titled ‘Resilient Cotton Farming Systems’ explicitly aimed at addressing issues of cotton sustainability in a variable and changing climate. As this is only a new initiative, projects focussing on climate change are still being developed. The Cotton Research and Development Corporation have also invested in projects investigating a cotton system’s contribution to greenhouse gases and potential mitigation strategies.

Table 3.1: Summary of climate change adaptation options for the cotton industry indicating whether the option 1) has already been assessed or is a remaining knowledge gap, 2) is highly feasible, 3) would be feasible / effective immediately, or 4) should be a high priority for research, assessment and implementation in developing adaptation strategies.

Adaptation options	Options already assessed	Options with high feasibility	Immediacy	Priority activities
Policy/Industry				
Develop linkages to existing government policies and initiatives e.g. GGAP, Greenhouse challenge, salinity, water quality, rural restructuring	X	✓	✓	✓
Expansion of industry to other regions (including northern Australia)	✓	✓	X	X
Ensure communication of broader climate change information	✓	✓	✓	✓
Address community resilience to the effects of climate change on the cotton industry	X	✓	X	X
Maintenance of effective climate data distribution and analysis systems	✓	✓	✓	✓
Continue training to improve self-reliance and to provide knowledge base for adapting	✓	✓	✓	✓
Policy settings that encourage development of effective water-trading systems that allow for climate variability and support development of related information networks	✓	✓	✓	✓
Public sector support for a vigorous agricultural research and breeding effort with access to global gene pools	✓	✓	✓	✓
Maintain R&D capacity, undertake further adaptation studies which include costs/benefits and streamline rapid R&D responses	X	✓	✓	✓
Develop further crop systems modelling capabilities such as OZCOT and APSIM and quantitative approaches to risk management	✓	✓	✓	✓
Encourage appropriate industry structures to enable flexibility	X	X	✓	X
Encourage diversification of farm enterprises (other crops and livestock)	✓	✓	✓	✓
Ensure support during transition periods caused by climate change and assist new industry establishment	X	✓	X	X
Investigate trends and extremes resulting from climate change both regionally and globally for production and explore implications for our markets and impact on our competitors	X	X	X	X
Altering transport and market infrastructure to	X	✓	X	X

Adaptation options	Options already assessed	Options with high feasibility	Immediacy	Priority activities
support altered production regimes caused by climate change				
Encourage financial institutions to be responsive to changing industry needs	X	✓	X	X
Continuing commitment from all levels of government for pest, disease and weed control including border protection	✓	✓	✓	✓
Introduction of climate change adaptation (including minimising industry's greenhouse carbon footprint) into Environmental Management Systems (BMP Cotton)	✓	✓	✓	✓
Auditing energy use in cotton farming systems including developing benchmarks and tools to assess and improve efficiency and being ready to exploit opportunities such as bio-diesel	X	✓	X	X
Provide information that acknowledges that exiting industry is a legitimate adaptation strategy	X	✓	X	X
Crop and farm management				
Maintain farm profitability	✓	✓	✓	✓
Development of participatory research approaches to assist pro-active decision making on-farm	✓	✓	✓	✓
Improve nitrogen use efficiency of cotton crops	✓	✓	✓	✓
Develop practices to take advantage of increased temperatures especially at the start and end of the growing season to raise yields	✓	✓	✓	✓
Improved management options in limited water situations (alterative irrigation systems; row configurations, irrigation scheduling strategies)	✓	✓	✓	✓
Research and revise soil fertility management (fertilizer application, type and timing, increase legume phase in rotations) on an ongoing basis	✓	✓	✓	✓
Alter planting rules to be improve yield and quality	X	✓	✓	✓
Expand routine record keeping of weather, production, degradation, pest and diseases, weed invasion	✓	✓	✓	✓
Avoiding resistance of pests (both insects and weeds) through appropriate integrated pest and weed management systems to maintain transgenic technologies	✓	✓	✓	✓
Maximise whole farm water and crop water use efficiencies	✓	✓	✓	✓
Tools and extension to enable farmers to access climate data and interpret the data in relation to their	X	✓	✓	✓

Adaptation options	Options already assessed	Options with high feasibility	Immediacy	Priority activities
crop records and analyse alternative management options.				
Develop tools to measure crop water use accurately	✓	✓	✓	✓
Develop cotton systems that are earlier maturing, use less water and allow more crops to be grown in rotation	X	✓	X	X
Link on-farm adaptation with catchments impacts	✓	✓	✓	✓
Climate information and use				
Improve dynamic climate modelling tailored towards decision making in agriculture	✓	✓	✓	✓
Provision of information to cotton growers of the likely impacts at their business level (downscaling climate change predictions to regional scales)	X	✓	✓	✓
Incorporate seasonal forecasts and climate change into farm enterprise plans so as to be able to readily adapt	X	✓	✓	✓
Maximise utility of forecasts by RD&E on combining them with on-ground measurements (i.e. soil moisture, nitrogen), market information and systems modelling.	✓	✓	✓	✓
Warnings prior to planting of likelihood of very hot days and high erosion potential	✓	✓	X	✓
Enhance capacity to forecast pest pressures (weeds, invertebrate and diseases)	X	✓	✓	✓
Water resource issues				
Further improvements in water distribution systems (to reduce leakage and evaporation), irrigation practices such as water application methods, irrigation scheduling and moisture monitoring to increase efficiency of use	✓	✓	✓	✓
Maintain access rights to water	✓	?	✓	✓
Develop water trading system (and associated information base) that can help buffer increased variability	X	✓	✓	?
Maximise water capture and storage on-farm – needs R&D and policy support	✓	✓	✓	✓
Develop greater understanding of water availability in relation to river flows	✓	✓	✓	✓
Managing pests, disease and weeds				
Improve pest predictive tools and indicators	✓	✓	✓	✓
Improve quantitative modeling of individual pests to	X	✓	X	X

Adaptation options	**Options already assessed**	**Options with high feasibility**	**Immediacy**	**Priority activities**
identify most appropriate time to introduce controls				
Further development of Area-wide Management operations	✓	✓	✓	X
Further development of Integrated Pest Management	✓	✓	✓	✓
Improved monitoring and responses to emerging pest, disease and weed issues	✓	✓	✓	✓
Crop breeding				
Selection of varieties with appropriate, heat shock resistance, drought tolerance, higher agronomic water use efficiency, improved fibre quality, resistance to new pest and diseases (including introgression of new transgenic traits).	✓	✓	✓	✓
Ongoing evaluation of cultivar/management/climate relationships (including investigations in higher CO_2 environments) on both yield and quality	✓	✓	✓	✓

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4: RICE

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Key Messages:

- Limitations in projected irrigation water supply under climate change are likely to have a significant impact on Australian rice production, which is totally dependent on supply of irrigation water.
- Evapotranspiration rates over the rice-growing period are projected to increase over the next century, however the effect on total water demand of rice crops may be balanced in part by faster development of the crop and a shorter growth cycle.
- The risk of low-temperature damage during reproductive phase, one of the major historical limitations to rice production, is likely to be reduced under climate change projections. While the net impact of increased temperatures and CO_2 on rice is largely unknown in the Australian environment, climate change may increase the risk of heat-damaged crops (not currently a major issue).
- There is some scope to further adapt existing rice production methods to reduce irrigation demand – through reduction in the duration of ponding via operational (direct drilling) and breeding (yield/duration) means, as well as reduction in deep percolation losses through enhanced definition and regulation of rice-suitable soils. Significant improvements in water productivity will be difficult to achieve under the existing production system, and the immediate consequence of less water will be less rice. However aerobic and alternate-wet-and-dry (AWD) rice may present the Australian rice industry with new options, and may allow increased water productivity (kg grain/ML) in a changing climate. The viability of these novel rice production systems for the Australian environment warrants immediate research.
- Potential new methods of rice production (aerobic culture) may allow expansion of rice growing to new areas or regions.
- The rice industry has been highly successful in increasing water-use efficiency over its history, and must continue to do so in adapting to climatic change. Rice farmers will need to consider a wide range of potential farming system changes (new varieties/crops, rotations, water priorities, irrigation methods, farm layouts, use of seasonal climate forecasts in management) to adapt to predicted changes in on-farm climate and water supply over the coming century. Research into the viability of new farming system ideas, in comparison with traditional systems, is urgently needed to allow for future farm planning.

Introduction

Rice was first commercially grown in Australia in the early 1920's near the townships of Leeton and Yenda in the New South Wales Riverina. The current industry in Australia has a restricted geographical range, encompassing the irrigated regions of southern NSW and northern Victoria (Figure 4.1). Rice growing is concentrated in this area due to the availability of irrigation infrastructure, historical availability of water, large areas of flat land, suitable clay-based soils and the development of storage and milling infrastructure in or near the regional towns. Also, institutional policies restricted rice growing to the irrigation areas and districts until the 1980s.

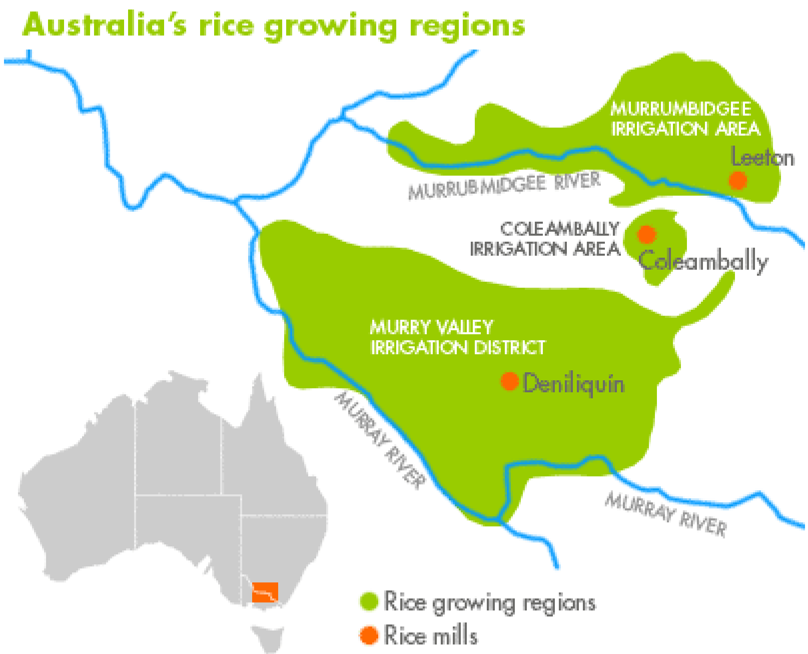


Figure 4.1: Australia's Rice-growing Regions (courtesy of the Ricegrowers Association of Australia)

Economic value

In a year without climate-induced restrictions the Riverina region produces around 1.3 million tonnes of rice. Of this, 85% is exported and 15% services the domestic market. In such a year, the industry earns around $800 million in revenue, which includes nearly $500 million from value-added exports. Rice is Australia's third largest cereal grain export, and the ninth largest agricultural export (all data from Sunrice)

Annual rice production internationally is approximately 550-600 million tonnes (Maclean *et al.* 2002), making Australia a relatively small player, however Australia grows high quality rice to service specific markets. Also, only 25 million of the 600 million tonnes of world annual rice production is traded outside the country of origin. Therefore, although Australian rice only represents around 0.2% of world rice production, exports represent over 4% of world trade of medium grain rice (Sunrice). The sustainability of a large number of regional towns and communities in the Riverina is highly-dependant on rice-based farming systems (Linnegar and Woodside 2003).

Agronomy

Australia's rice-growing region experiences evenly-distributed annual rainfall, with the mean annual average ranging between 350 – 450 mm per annum. Rice is a summer grown crop, sown in windows according to variety from mid-September to mid November. The crop has a growing season of approximately 6 months, and due to the relatively low rainfall the crop is totally reliant on the supply of irrigation water during this period. Rice costs roughly 1150 $/ha to establish and grow compared with $250 for dryland wheat, (NSW DPI Farm Enterprise Budget Series 2005/2006), hence farmers are conservative in estimating the total rice area to plant, due to the economic consequences of running out of water. Large yield losses can be expected if ponding cannot be maintained for the required length of time (Heenan and Thomson, 1984).

Rice is grown in rotation with a range of other species including cereals, oilseeds, pulses and pastures, and is only one component in a diverse farming system. It is however the dominant broadacre crop, in good seasons occupying 10–25% of the landscape in the major irrigation regions for about 6 months each year, and accounting for 50–70% of the total irrigation water use (Humphreys *et al.* 2006).

At various stages throughout the year the farmer must make decisions on the proportion of area cropped and crop mixes based on available water allocation information. Certain restrictions apply. For example, the area of rice that may be planted at any time is limited to 69 ha or 30% of the approved rice-growing land, whichever is greater. Historically, approved rice-growing soils were defined physically based on clay content (Humphreys *et al.* 1994). Current rice soil suitability criteria also incorporate electromagnetic surveying and measurement of soil exchangeable sodium percentage (a measure of soil sodicity) (Beecher *et al.* 2002). Soils with potentially high deep percolation characteristics are therefore removed from rice growing. Table 4.1 shows the average gross-margin returns and water-use efficiencies for crops in the Murrumbidgee Valley (2005/2006). Water-use efficiency is defined here as the gross marginper ML irrigation water used.

From the perspectives of both gross margin and water-use efficiency, farmers seeks to maximise their planted rice area (Table 4.1).

Table 4.1: Murrumbidgee Valley average Figures for 2005/2006 (source :NSW Department of Primary Industries "Farm Enterprise Budget Series")

Crop	Gross Margin ($/ha)	Water Use Efficiency ($/ML)
Aerial-sown medium-grain rice	1550	111
Irrigated Soybeans	636	79
Irrigated Wheat	263	75

The rice produced in Australia is mostly of the *Japonica* type, which are relatively soft-cooking medium and short-grain types as distinct from *Indica* (predominantly firm-cooking long-grain types) which is grown throughout the tropical world. Japonica rice is more suited to the temperate micro-climate of Australia's rice growing region. Even though Japonica rice is more tolerant of cooler conditions, cold induced spikelet sterility remains one of the major constraints to yield in the region (Humphreys *et al.* 2006). Average Australian rice yields are amongst the highest in the world, averaging 10.4 tonnes grain yield per hectare in 2003 (Humphreys *et al.* 2004)

Water requirements

The long term average ET_o at Griffith is 1160 mm (11.6 ML/ha) over the rice season, while rain averages 160 mm (Humphreys and Meyer 1996). This therefore means that on average rice requires 1000 mm of irrigation water to meet net evaporative demand (Humphreys 1999). The district average irrigation water requirement of 1400mm (14 Ml/ha) leaves a balance of 400mm which is lost between deep drainage, runoff, and on-farm channel losses. In hot, dry years the average irrigation water requirement can increase from 14 Ml/ha to in excess of 16 Ml/ha. Falling water tables due to drought may also result in similar increases in rice irrigation water requirements, particularly on more marginal rice soils where the presence of shallow water tables, rather than low soil hydraulic conductivity, limit percolation. (Arun Tiwari, Coleambally Irrigation Limited, pers com). Average field water productivity (kg grain per ML applied irrigation water) of the total NSW rice crop roughly doubled over the period 1980–2000. This was primarily due to increased yields (breeding, management, nitrogen management, water management (Lacy 1994)), and partly due to reduced water use (Humphreys and Robinson 2003) brought about by a range of industry-imposed restrictions and regulations.

Water Supply

Surface water is the major source of irrigation water supply for rice-growers in the Riverina (river water, pumped directly or diverted into canal systems), although some groundwater is also used (Humphreys *et al.* 2006). Farmers own licences entitling them to a certain water allocations, however allocation amounts are regulated according to annual dam supply. In brief explanation, water licence entitlements are divided into high and low security. A ‘high security’ licence guarantees the licensee of receiving their full entitlement in 99% of seasons. High security licences are generally issued for town water supplies, stock and domestic needs, industrial uses, as well as permanent plantings like vineyards and orchards. The remaining water available for use after environmental demands and high security allocations have been met, is termed ‘general security’. This is made available to farmers growing annual crops such as rice, wheat, soybeans and pastures. General security allocations are by definition subject to much greater variation from vagaries in climate, represented by in inflows into the storage dams (Blowering, Burrinjuck, Hume, and Dartmouth). (For more details see http://www.dlwc.nsw.gov.au/water/index.shtml).

The irrigation season in the Riverina rice-growing districts is from July through to the following May/June. The first general security announcement is made in the middle of August and is based on current dam levels and minimum historical inflows (99% reliability). There is hence a 99% chance that more water will become available for allocation as the season proceeds (Khan *et al.* 2004). The announced percentages apply to the individual river valley and are made by the NSW Department of Water and Energy each subsequent month or on the occasion of significant inflows into the dams. The announcement is in the form of a percentage, referring to the proportion of the irrigator’s total licensed amount that is guaranteed to be available by the end of February. Each month, the announced allocation can, in theory, only be increased or remain the same.

Currently, for general security irrigators there is an allocation ‘cap’ of 83% of the total licence amount, and an allowable carry-over of 15% to the following year, so long as the carry-over amounts do not increase the subsequent year's allocation to above 100%. (Murrumbidgee Allocation Plan 2004/05, Murray and Lower Darling Allocation Plan 2004/05).

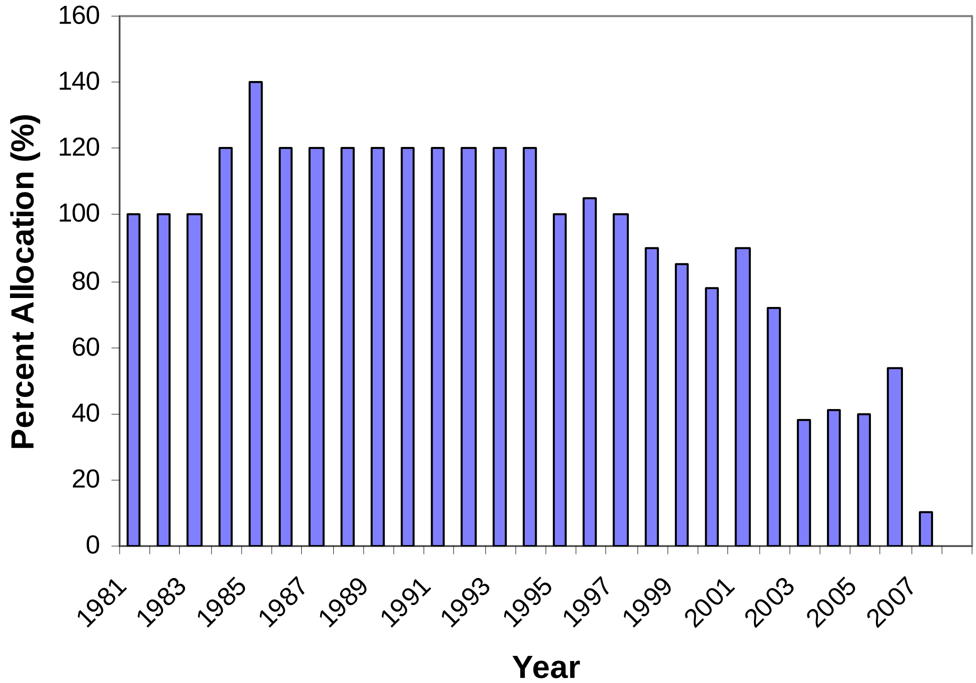


Figure 4.2: Irrigation water allocations (percentage of licensed quota) for Murrumbidgee Irrigation Area (MIA), 1980/81 – 2007/08.

As depicted in Figure 4.2, rice-growers have experienced a precipitous drop in irrigation water allocations over the last decade in stark contrast to a history of receiving 100% of licensed allocation every season, if not more.

Factors affecting current water supply

In Australia, the supply of water to rice-growers is not affected by climatic factors alone. Environmental policies and the National Competition Policy have also resulted in decreased water availability to irrigators, and threaten increased water prices in the future (Humphreys and Robinson 2003).Worldwide, water for agriculture is becoming increasingly scarce (Rijsberman 2006). Various sectors with increasing demand (urban, industrial, environmental) competing for this limited resource are likely to exacerbate the impact of climate change effects on water supply to rice-growing areas globally (Bouman *et al.* 2007).

Climate Change Impacts

Irrigation Water Supply

Practically all of Australia's rice is grown in conditions of shallow (10cm) ponded water. Consequently, total rice production in Australia has a strong linear relationship with total irrigation water allocations in the rice-growing districts (Figure 4.3). Deviations around this linear relationship are likely due to a range of other less influential factors affecting rice production such as temperatures, disease, and market dynamics.

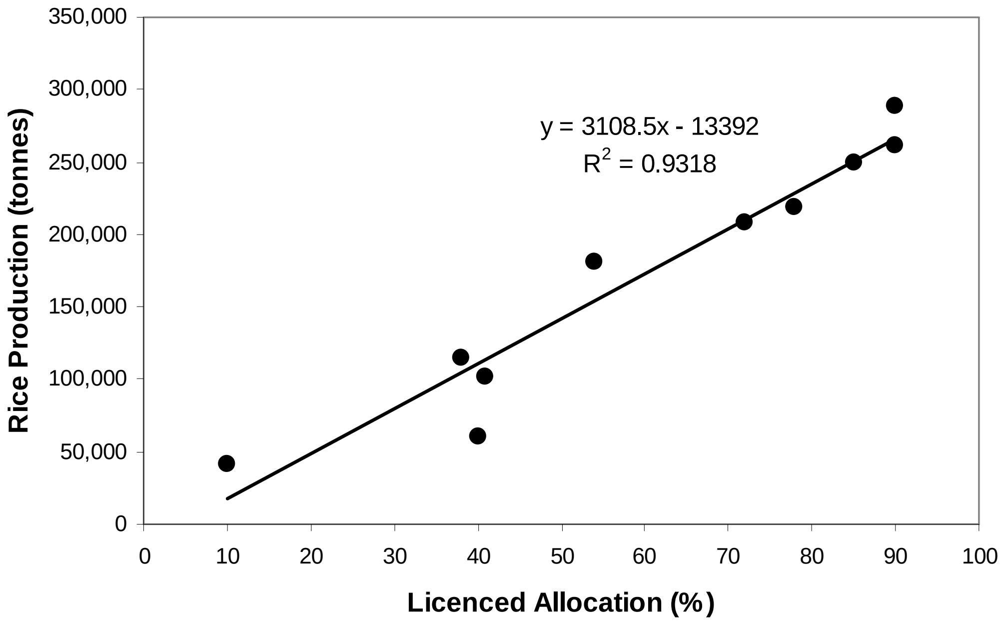


Figure 4.3: The relationship between annual irrigation water allocation and annual rice production for the Coleambally Irrigation Area, NSW, (1998-2007) (statistical data provided courtesy Roger Clough, Grower Services, SunRice, Leeton).

The effect of projected climate change on irrigation water supply to the Riverina rice growing areas is therefore a dominating factor in assessing climate change impacts on rice production. Recent climate change projections suggest 16-25% reduction in average Murray-Darling stream-flows by 2050 and 16-48% reduction by 2100 (Pittock 2003; Christensen *et al* 2007). This is likely to have dramatic implications for irrigation water allocations in the Riverina (Jones and Pittock 2003). The strong relationship between available irrigation water and production (Figure 4.3) would suggest significant impacts in future production in response to likely declines in average stream-flow, however there are a number of other confounding factors relating to extent of changes in competing water sectors (i.e. domestic, environmental allocations, industrial etc) (Adamson *et al.* 2007; Humphreys and Robinson 2003).

A more updated assessment of stream flow is expected from the CSIRO Land & Water "Murray Darling Basin Sustainable Yields Project" at the end of 2007. This project will assess a range of projected future climate scenarios (using the 4th IPCC Report archived modelling results for 15 General Circulation Models (GCMs)) and potential future development scenarios (farm dams, surface and groundwater extractions, commercial plantations, domestic requirements etc) for all major catchments within the Murray Darling Basin, and report on surface water and ground water availability impacts both in terms of average yields but also variability (http://www.csiro.au/partnerships/MDBSY.html).

Irrigation Water Demand

Seasonal irrigation water requirements in the Riverina have historically exhibited high levels of variability. Annual water requirement for rice crops to meet evapotranspiration can rise above the mean value by up to 30% (up to 16 Ml/ha with a mean of 12 Ml/ha, (Peter Sheppard rice farmer, pers com)). Modelled annual whole-of-farm water requirement for a sample farm at Kerang, Vic, growing perennial pasture was noted to vary between approximately 210 Ml to 370 Ml, around an average of approximately 290 Ml over the period 1975-1996 (Jones 2000), a variation of roughly 30% either side of the mean.

A global modelling study on the impacts of climate change on irrigation water requirements found that significant variation could be expected geographically (Döll 2002). For South-Eastern Australia, this study found that the projected impact of climate changes on irrigation demand is smaller than the existing interannual climate variability. Figure 4.4 shows the comparison between historical pan evaporation at G riffith (1900-2006), and projected pan evaporation at Griffith using the HadleyCM2 GCM for low and high forcing climate change scenarios (IPCC B1 and A1F1 respectively) for (a) 2030 and (b) 2070. (Gaydon & Crimp, in prep)

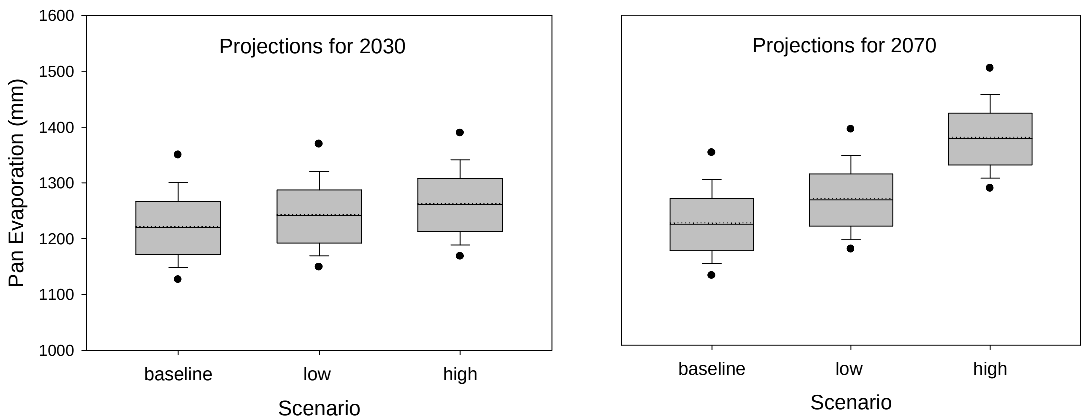


Figure 4.4: Figure 4 Historical and projected cumulative seasonal pan evaporation over the rice growing season (15 October – 15 April) for Griffith. Projections developed using the HadleyCM2 GCM for low and high forcing scenarios (IPCC B1 and A1F1 respectively) for (a) 2030 and (b) 2070. 'Baseline' refers to historical records. Within the grey boxes, the dotted line is the mean, the solid line the median.

We could find no published research on potential impacts of climate change scenarios on Australian water use in rice crops, however international research suggests that a combination of increased evaporative demand and decreased rainfall would result in average Sri Lankan paddy water requirement increasing by 13-23% depending on the GCM forcing scenario (De Silva et al. 2007).

Given that Australia represents a markedly different rice-growing environment, and is less reliant on in-crop rainfall, further research into this issue is required.

In summary we can expect that climate change will increase the irrigation water demand of rice crops, however mean increases will most likely not exceed the range of historically-experienced variability although individual years may exceed the range. Extending the projection to 2070 could see some large increases in water demand if a high forcing projection is considered. Also, projected decreases in regional rainfall (Christensen, 2007) could also see the contribution to total rice water requirement from irrigation water increase as the rainfall contribution decreases, thereby further adding to irrigation water demand.

Increased temperatures

There is little published work on impacts of increased maximum and minimum temperatures on Australian rice varieties, however there is substantial literature from international research. Flowering and booting (microsporogenesis) are the most susceptible stages of development to temperature in rice (Satake and Yoshida 1978; Farrell *et al*. 2006a). Studies detailed in Satake and Yoshida (1978) indicate that spikelets which are exposed to temperatures >35 ^{o}C for about 5 days during the flowering period are sterilized and do not seed. Jagadish *et al*. (2007) in greenhouse experiments with both *indica* and *japonica* genotypes, found that less than one hour of exposure to temperatures above 33.7 ^{o}C was sufficient to induce sterility. However it is important to note that the temperatures quoted in each of these studies refers to the actual temperatures experienced by the spikelets, not the ambient temperature. There is generally significant cooling at the spikelet due to transpiration within the canopy, particularly in the low humidity rice growing environments of Australia. This has been measured at 4 - 6.8^{o}C under conditions of 34.8ºC ambient temperature and 20% relative humidity in Australian environments (Matsui et al. 2007). Australian rice crops regularly receive ambient temperatures in excess of 35 ^{o}C during this period, hence if it were not for the low humidity and consequent evaporative canopy cooling, it appears that high temperature sterility issues could be a major limiting factor for rice production in Australia. There is the possibility that climatic change could produce even greater cooling differentials.

However despite this, the potential for greater extremes in maximum temperatures under climate change (Christensen et al. 2007) still pose a risk to rice at flowering and booting stages in Australia. Each of these periods lasts for around 5 days in most rice genotypes, and in the Riverina occurs sometime between 5th Jan – 15th Feb (Farrell et al. 2006b). Figure 4.5 (from Gaydon & Crimp, in prep) shows the significantly increased likelihood of dangerously high canopy temperatures (> 35 ^{o}C) during this period, assuming a 6^{o}C cooling within the canopy at time of maximum temperature. The risk of high temperature more than doubled for flowering rice crops at Griffith by 2070. There is also evidence that in addition to large negative yield impacts from short periods above very high temperatures, damage may be cumulative with duration of exposure above certain lower, threshold temperatures. These will vary between cultivar (Jagadish et al. 2007), however this has not been considered in this analysis.

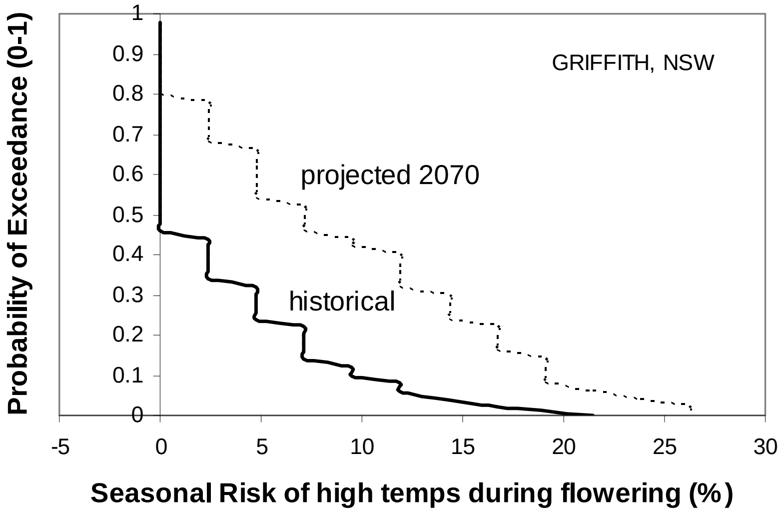
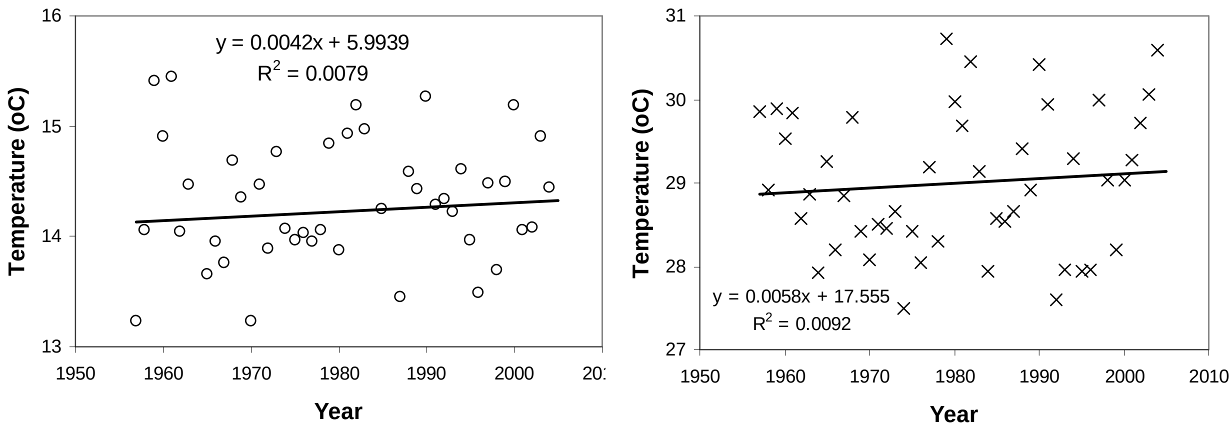


Figure 4.5: Effect of climate change scenarios on risk of experiencing dangerous high temperatures at rice flowering/booting for Griffith. Warming projection developed using the HadleyCM2 GCM for a high forcing scenario (IPCC A1F1) (Gaydon & Crimp, in prep).

It is suggested that increases in average minimum temperatures may be more significant in overall terms than increases in maximum temperatures (Peng et al. 2004). In trends at the International Rice Research Institute (IRRI) Farm, Los Banos, Philippines, between 1979 and 2003, rice grain yield declined by 10% for each 1°C increase in growing-season minimum temperature in the dry season, whereas the effect of maximum temperature on crop yield was insignificant. Decreases in rice yields are attributed to increasing night-time temperatures associated with global warming. IRRI annual mean maximum and minimum temperatures increased by 0.35°C and 1.13°C respectively, during the 25-year sampled period. This equates to 0.014 and 0.045 ^{o}C per year for average maximum and minimum temperatures respectively. The increase in minimum temperature was 3.2 times greater than the increase in maximum temperature, which is consistent with the observation that minimum temperature has increased approximately three times as much as the corresponding maximum temperature from 1951 to 1990 over much of the Earth's surface (Karl 1991). Figure 4.6 shows both the observed trends in average minimum and maximum temperature in the Riverina over the rice growing period (Oct – April) between the years 1957 and 2005.

Past observations show a pattern of higher average maximum temperatures associated with drought years (ie. less cloud cover) and lower average maximum temperatures associated with years of above average rainfall (ie. more cloud cover). Hence the temperature trends evident may be substantially a function of more drought years in the second half of the record compared with the first. Whilst a strong correlation exists between droughts and increased average maximum temperatures recent work by Nichols (2004) has demonstrated that over the last 50 years droughts have, on average, been hotter.

We can find no published evidence to show trends observed by Peng et al (2004) are mirrored in Australian rice yields, however similar trends have been observed elsewhere in the world (Pathak and Ladha , *et al.* 2003). There may be different factors at play in different environments, however the observed IRRI trend suggests that further investigation may be warranted for projected Australian climate scenarios.



(a) (b)

Figure 4.6: Trends in average (a) minimum and (b) maximum temperatures during rice season (Oct-April) at Coleambally (1957- 2006).

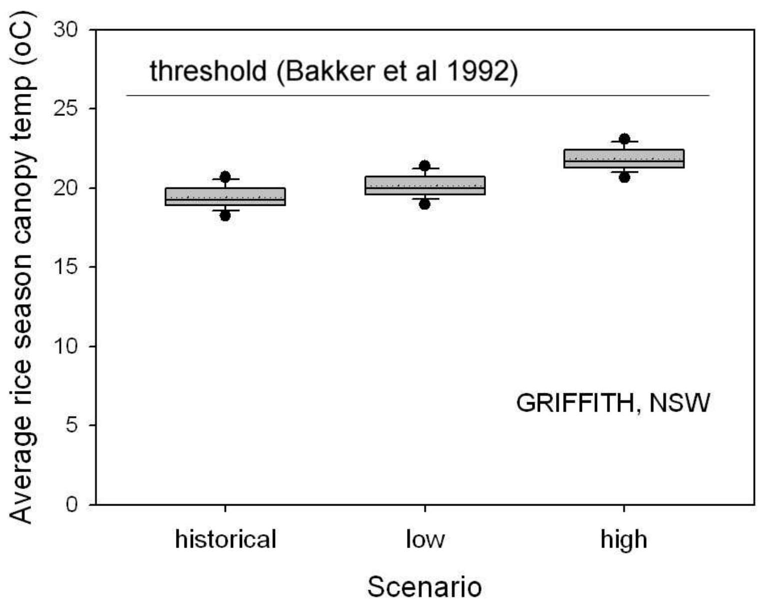


Figure 4.7: Average canopy temperature during rice growing season for Griffith under historical climate, and low/high climate change forcing scenarios using the HadleyC2 GCM (scenarios are IPCC b1 and a1f1), assuming a canopy cooling of at least 4 °C (Matsui et al 2007) applied to maximum daily temperatures. The threshold is average season temperature (Peng *et al,* 1995) above which a negative yield response could be expected.

There is general agreement that increased average temperatures will have a negative effect on rice yields internationally, with yield decreases due to temperatures alone (in isolation from CO_2 increases) estimated to range between 5 and 10% per 1°C rise in average season temperatures in some areas (Peng *et al*. 1995; Baker *et al.* 1992; Baker and Allen 1993) . Peng *et al* (1995) suggested a negative yield response to increasing average rice season temperatures above a threshold of 26 °C. In

Australia, the range of average temperature during rice growing season is shown in Figure 4.7 for historical and high & low forcing climate change projections.

Australia and other temperate rice growing zones of the world may experience an increase in rice production with temperature, as climate changes increases average canopy temperatures which are currently below the 26 ^{o}C threshold (Peng *et al.* 1995). Note that this threshold was reported for indica varieties, and on the basis of no further information this analysis assumes it is the same for japonica varieties. As can be seen in Figure 4.7, if the average maximum daily temperatures are reduced according to the evaporative canopy cooling effect measured by Matsui et al (2007) of 6 ^{o}C, Australian rice production seems a considerable way from experiencing yield reductions due to climate change effects. Figure 4.7 suggests that this would be the case even under the highest climate change forcing scenario for 2070, if the threshold suggested by Peng *et al* (1995) applies. There is further evidence that some Australian varieties have other physiological features/characteristics conferring tolerance to high temperatures which may increase the thresholds (Matsui et al. 2007), however this is a research area in which information is limited and further work is warranted to define these mechanisms and ensure future varieties have equal or improved tolerance levels. Baker and Allen (1993) suggest potentially reduced evaporative cooling of the canopy under increased CO_2 scenarios. It is also unknown whether the canopy cooling effect detailed by Matsui et al (2007) would apply to aerobic and AWD rice cultures, and the extent to which this would effect high temperature risk in this culture.

There is evidence of a likely strong interaction between temperature and CO_2 which is discussed in the Combined Temperature and CO_2 Effects section below.

Cold temperature damage and frost risk

There is presently significant risk of low-temperature damage during the reproductive stage in rice under Australian conditions. Low minimum temperatures can lead to pollen sterility and low yield in high N status crops. Minimum temperatures less than 17-19 ^{o}C during panicle development are considered dangerous (Farrell *et al*, 2006b). The development of semi-dwarf varieties allowed the effective use of deep floodwater levels as a management strategy during this period as a management strategy to minimise risk by inundating the developing panicles (Williams and Angus 1994). At critical times, paddy water may be 5-7 ^{o}C warmer than the ambient air conditions.

The coldest temperature often occurs just before dawn. The temperature of the rice plant components exposed to the ambient air has been shown to be practically identical to ambient air temperatures at this time (Williams and Angus 1994). The probability of encountering such ambient air temperatures during flowering are around 20-25% in the Griffith area, for the most commonly-planted cultivar Amaroo (Farrell *et al*. 2006b). The degree to which projected climate change scenarios might impact that risk is shown in Figure 4.8 (Gaydon & Crimp, in prep).

Figure 4.8 shows projected climate change (IPCC A1F1 scenario, 2070) is likely to reduce the risk of low temperature occurrence at rice flowering by roughly one third. Currently this risk is mediated by the use of increased water levels (20cm) over this period, however adaptive options such as aerobic rice (see section below under Adaptation Options) do not have this protection and the projection in this risk is relevant to deliberations on this option.

There is evidence that frost risk may increase with climate change in southern Australia, hence further analysis of this matter is recommended.

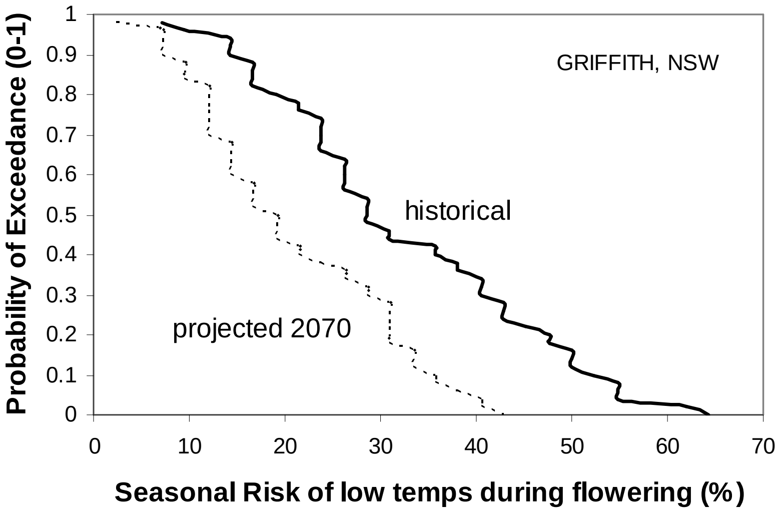


Figure 4.8: Risk of ambient temperatures below 15 °C during rice flowering time under historical and projected climate for Griffith, 2070 (general period of rice flowering is defined as 5th Jan – 15th Feb (Farrell et al, 2006b), however in any given year occurs over only five days). Risk per season is defined as the number of days per 5th Jan – 15th Feb period in which minimum temperature falls below 15°C. Warming projection developed using the HadleyCM2 GCM for a high forcing scenario (IPCC A1F1).

CO_2 fertilisation

Several free-air CO_2 enrichment (FACE) experiments have been conducted with rice, although none in Australia. Recent experiments in Japan and China using Japonica cultivars found that crop response to elevated CO_2 was associated with N uptake, and varied throughout the season (Kim *et al*. 2003; Yang et al. 2007). For CO_2 environments 200 ppm greater than ambient Kim et al recorded an average 15% increase in rice grain yield when N was in good supply, less for low N treatments. They found that green leaf area index response to increased CO_2 was positive during vegetative stages and negative after panicle initiation. This phenomenon was also observed in the Chinese experiments, with researchers suggesting that the recommended rates, proportions and timing of nitrogen application should be reconsidered under increased CO_2 to take full advantage of early uptake capacity and also facilitate subsequent N uptake (Yang et al. 2007). This study reported a rice grain yield increase of 13%. There is evidence from experiments in the Philippines that even higher CO_2 concentrations (300 ppm above ambient) can result in greater rice yield increases of (27%, (Ziska et al. 1997)). Note that mid-range projections of CO_2 in 2100 are about 350ppm higher than present.

The implications of an increase in atmospheric CO_2 for rice production under Australian conditions are not known, however it would seem reasonable to assume similar potential rice yield increases as those observed in the Japanese and Chinese studies.

Combined Temperature and CO_2 Effects

Several studies have shown that high air temperatures can reduce grain yield even under CO_2 enrichment (Baker and Allen 1993; Ziska *et al*. 1997). There is also evidence to indicate that the relative enhancement of rice yields due to CO_2 fertilisation is gradually reduced with increases in air temperatures (Matsui et al. 1997), as the critical temperature for spikelet sterility is reduced.

It is difficult to make inferences on the implications for Australian rice production particularly as some studies have reported significant variance in the response of different cultivars to CO_2 fertilisation (Baker 2004; De Costa et al. 2007; Moya et al. 1998; Ziska et al. 1996). A modelling study covering a diverse range of agro-climatic zones in India, (Aggarwal and Mall 2002) found that climate change outcomes on rice grain yield were positive regardless of the uncertainties and climate change forcings, with average rice grain yield increases ranging from 1 – 38%. In contrast, negative trends in rice yields were found in a modelling study in India due to increases in minimum temperature and decreases in incident radiation (Pathak et al. 2003). This result was supported by observed data, and the researchers also suggested that these declining trends should be taken as an indication of a future problem in food security.

Given the disparity in existing international studies, and the lack of published Australian studies it is difficult at this point to make any informed judgement on the combined effect of increased temperature and CO_2 concentrations on Australian rice production.

Summary of Climate Change Impacts

The largest impact from projected climatic change on Australian rice production is likely to be from reduced supply of irrigation water. Projected reductions in Murray-Darling stream-flows of 16-25% by 2050 and 16-48% by 2100 are likely to result in similar levels of reduction in rice production, under current production and water use systems. A key question relates to the projected increase in variability of water supplies, how often significant rice plantings will be possible, and hence how this will affect the cost/benefits of maintaining current rice production infrastructure. Farming systems changes in response to a reduced and more variable water supply (ie changed rotations, irrigations methods, crops, layouts etc) could see additional reductions in rice production, however the costs/benefits of various adaptation options are currently unknown and this is a major research area for irrigated farming in the Riverina.

The impacts on rice yields in the Australian situation from projected CO_2 fertilisation and changes in temperature are much more uncertain, and require further research. It would appear that yield reductions due to extreme high temperatures presents a possible risk, given the current high ambient temperatures during rice microspore and the likelihood of increased temperature extremes in combination with potentially reduced evaporative cooling of the canopy under increased CO_2 scenarios. It is unlikely that increases in average temperatures over the growing period will present significant production risk, as considerable buffer already exists between current average temperatures and the reported average temperature thresholds for incurring yield losses. Increased temperatures associated with climate change may reduce the risk of low temperature damage during microspore – one of the largest limitations to rice production in Australia currently.

Adaptation Options

Current Options for Dealing with Climate Variability

Cropping Area Modification

The process of irrigating crops is in itself an option for dealing with climate variability. When rainfall is less forthcoming, extra irrigation water is applied to meet the deficit. Similarly, less irrigation water is required in seasons with higher on-farm rainfall. Hot, dry growing seasons result in increased water demand, and historical climate variability in the rice-growing districts has been characterised by significant variance in seasonal water requirements to produce a rice crop. There are existing options for managing this variability in water demand. When calculating areas for sowing to rice, farmers often employ a small 'buffer' in their calculations to account for the possibility of encountering greater than average evaporative demand in the coming season. For example, if a farm has a historical average water requirement of 12 Ml/ha to produce a rice crop, the farmer may utilise a figure of 14-15 Ml/ha in calculating the area serviceable from his irrigation water allocation. Hence,

1000 Ml allocation / 14 Ml/ha = 71.5 ha

In this example, the farmer would conclude he cannot sow any more rice than 71.5 ha. In this way, if the season water demand runs higher than average, he will only be short of water on the most extreme of years. If the demand runs to average levels then he will have excess water, which can be used elsewhere or used as 'carry-over' for the subsequent winter crop or following years summer crop. Alternatively growers might adopt a strategy of sequential sowing, increasing over the planting window as progressive allocation increases are made and are anticipated into the future.

Purchase/sale of Water on Open Market

Water can be bought and sold on the open market, and represents an option for managing situations in which a growers encounters water shortages due to climatic variability. (for example see http://www.waterfind.com.au/)

Investment in more efficient irrigation technology

The majority of the other crops in the rice-growing districts are irrigated using surface irrigation methods (furrow, border-check bays) which may be inefficient on light-textured soils (Watson and Drysdale 2006) - although growers are moving to use higher flows and modified layouts to improve efficiency. With increasing pressure on decreasing water supplies, and likelihood of increased variability, some growers are now considering investment in more water efficient irrigation methods (pressurised systems, lateral move, subsurface drip) for non-rice crops on non-rice soils. For rice crops, shallow standing water is still necessary hence this potential adaptation does not apply, and improved surface application techniques/layouts are being pursued actively by growers (North 2007). However savings on other parts of the farm have the potential to affect water available for rice. All of the more efficient irrigation technologies require considerable initial investment and the cost-benefits are largely unknown. This represents a major research need in the Riverina irrigation districts, particularly as a function of soil type, climate-change scenario, water pricing scenarios, and crop price scenarios.

Flexible rotations

In managing variability in water supply, rice farmers have a high degree of inbuilt flexibility in their farming systems in comparison with operations based on permanent plantings such as grapes, fruit trees etc.. If water allocations are reduced, response strategies include:

- Reduce rice area sown (but still maximising potential rice areas with the limited water available) and leave larger areas of the farm in summer fallow. Generally, farmers will still aim to maximise their rice areas (see table 1, Introduction, for reasons) in accordance with available water. Spring watering of winter crops if rainfall is insufficient provided winter crop prices allow for good profit per hectare or megalitre.

- Reducing rice areas sown even further, and also sow other less water-intensive summer crops (eg soybean)

- Take the primary focus off rice, and plan to divert available water to subsequent winter cereals and pulses which require only supplementary irrigation in most/many seasons

- Sow no rice, and plan to hold the limited water allocation for potential sale later in the season when other more adventurous growers run out, and the water price is high.

The cost-benefits of each of these approaches is unknown, and represents a research need with the irrigated farming community.

Sowing winter crops directly after rice

During the rice phase of rotations, the soil is flooded until shortly before the crop matures in April, and hence effectively has a full profile of stored moisture at harvest. Growing winter crops immediately after rice harvest (direct-drilling) minimises the impact of climatic variability on the subsequent crop by providing a soil water buffer against the likelihood of a dry winter. Also, if not followed by a winter crop, the rice field will usually lie fallow over the winter until the next rice crop (depending on the rotation). In addition to increasing the grower's production, the planting of a sod-sown winter crop creates the capacity in the profile to capture winter rainfall instead of losing it as runoff or deep percolation (Humphreys et al. 2006).

Nutrient management adjustment

The MaNage Rice decision support software provides the farmer with guidance in determining nitrogen application rates (Angus et al. 1996; Williams et al. 1996) and is a key tool in managing climate variability for individual crops. The software allows the grower to download weather data, and conduct an analysis of various N management strategies as a function of sowing date, seasonal conditions, variety and water depth, based on assessment of N uptake at panicle initiation. It functions in much the same way as the Yield Prophet© software (Hunt et al. 2006) which aims to assist the farmer in better tailoring fertiliser requirements to individual seasons, and hence managing risk associated with climate variability. MaNage Rice is a product of CSIRO and NSW Department of Primary Industries and in the past updates were sent to all rice farm businesses on a CD.

Water Management

Low minimum (<15-18ºC) temperatures during the reproductive stage in rice can cause catastrophic damage to crops, particularly those with high N status (Williams and Angus 1994). One consequence of the historically variable climate in the Riverina is that low temperatures are occasionally encountered during this brief (5 day) period in the rice life cycle (see Figure 4.8). Due to plant-to-plant variation the five days at risk for a single plant equates to roughly a 10-14 day risk period for an individual crop. A management adaptation to this climate variability which allows growers to maintain high N-status (and hence potentially high yielding) rice crops is establishment and maintenance of increased depth over the critical danger period. The normal ponded water depth is often approximately 50-100 mm deep, however the depth is increased to around 200mm for two weeks, before returning to 50-100 mm for the remainder of the ponded period. The developing microspores are submerged or partially submerged to avoided low air minimum temperatures, using the thermal mass of the water as protection. High N applications have been shown to lead to high rice yields provided the microspores are protected from low temperatures in this manner (Williams and Angus 1994). This was a scientific development of truly massive impact in the Australian rice industry, is an integral component in the successful 'RiceCheck' recommendations (Lacy 1994) and the technology has had roughly 60% uptake by growers. The remaining 40% of growers encountered a range of difficulties including inability of system channel flow capacity to meet crop demand (sometimes out of farmer control).

Stubble retention

As detailed in the Grains chapter of this report, stubble retention for the purposes of soil moisture conservation is a widespread technique used to manage climate variability during non-rice phases in the rice-growing districts, however rice stubble is usually burnt prior to sowing of subsequent crops due to mechanical difficulties involved in sowing into the high-density biomass. Options are being researched to overcome this, such as the "Happy Seeder' (Sidhu *et al*, 2007). It is likely that climate change will drive continued changes in residue management practices over Australia as growers seek to conserve soil moisture and modify greenhouse gas emissions (Howden and O'Leary 1997)

Adaptation Options for Dealing with Climate Change

Altering varieties, planting times, nitrogen management and irrigation management to better match the new environments experienced under climate change is likely to increase yields compared to a non-action scenario. This can be viewed as the benefits of adaptation. When summarised over a large number of studies globally, the benefits of adaptation increase significantly with increasing levels of change (Figure 4.9). However, a similar analysis in wheat-based cropping systems suggests that there are limits to the benefits from management adaptations without making more fundamental system changes (Howden *et al.* 2007). In that case, the benefits were largely found with only a 2 to 3^{o}C increase in temperature and the associated changes in rainfall and CO_2. Rice systems appear to have a greater range of adaptive response with this being found up to 5^{o}C. However, many of the studies on which this analysis is based assume continuing availability of irrigation water and this may not eventuate. When options for fine-tuning the underlying rice-based system have been exhausted with high levels of climate change, there will be a need to adopt more systemic change such as moving to intermittently-irrigated systems or dryland systems. As stated by Humphreys *et al*. 2006, there is limited scope for further significant increase in irrigation or input water productivity by reducing water application under the current Australian rice farming system, and future savings must come from implementation of alternative, lower water-use systems with greater water productivity.

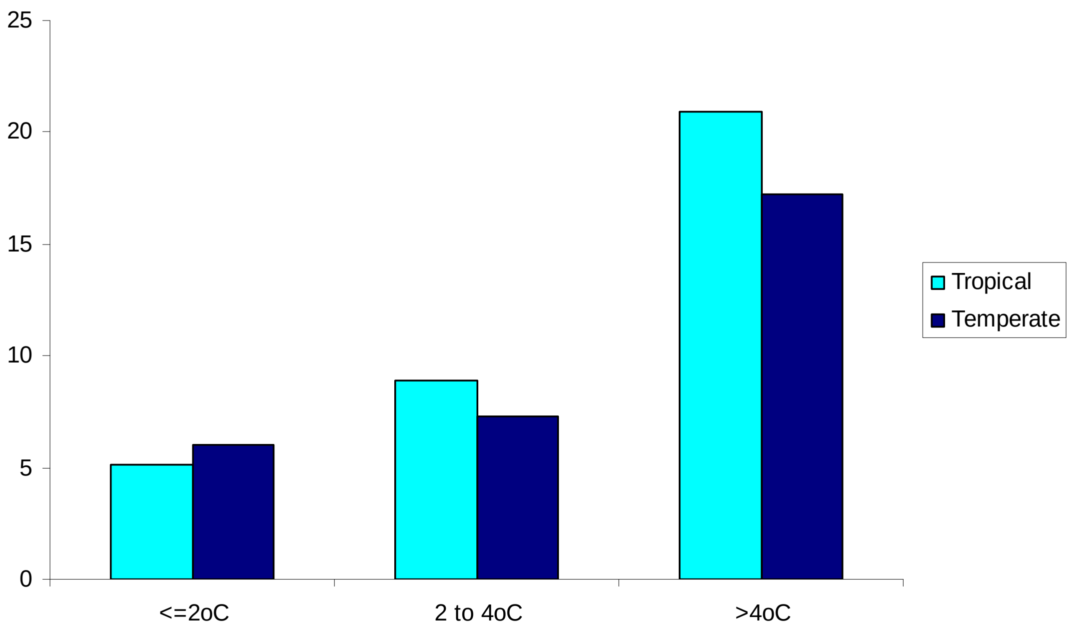


Figure 4.9: Mean benefit of adapting rice systems to impact of temperature and rainfall changes calculated as the difference between % yield changes with and without adaptation. Values are means for tropical and temperate systems. The mean benefit of adapting was not significantly different for temperate and tropical systems. Data sources are listed in Figure 5.2 of (Easterling *et al.* 2007). The temperature changes have associated changes in rainfall and CO_2 that vary between sites, scenarios and publications.

Reductions and increased variability in irrigation water supply are likely to represent the greatest challenge to the Australian rice industry from projected climate change. Hence water use efficiency measures in existing systems figure strongly in consideration of current options for dealing with the threat, in addition to future prospects for alternative systems. Options are considered below, firstly looking at potential water productivity improvements in existing systems, and secondly looking at a range of new ideas and potential modifications to systems which may hold the promise of enhancements to whole farm water productivity.

Increasing on-farm WUE within current farming systems

Better definition of rice-suitable soils

Historical methods of classifying rice-suitable soils depended on single-point paddock sampling. Groundwater recharge below ponded rice fields can be significant contributor to rising groundwater levels leading to soil and water salinisation. Reduced groundwater recharge is essential for sustainable rice-based, irrigated farming systems in southern Australia both from a groundwater/ salinity and a water productivity viewpoint. Until recently a soil was deemed as suitable for rice production if 1 soil profile per 4 ha contained 2 metres or more of continuous medium or heavy clay textured material. However it has been demonstrated that clay content alone is a poor predictor of groundwater recharge (Beecher *et al.* 2002). Electromagnetic induction surveys of rice fields can show variation in soil physico–chemical properties across rice fields. This allows the delineation of distinctly different areas of a field based on EM readings and allows accurate targeting of soil sampling and measurements. Current rice soil suitability criteria incorporates electromagnetic surveying and measurement of soil exchangeable sodium percentage (a measure of soil sodicity) enabling soils with potentially high percolation characteristics to be removed from rice growing. Consequently, there is significant potential to further increase water productivity through reduced water use in rice production through more accurate determination of the least permeable soils using the revised rice soil suitability criteria. This technology has had varied adoption at this point – in some jurisdictions electromagnetic surveying has been widespread whilst sodicity assessment is being adopted gradually. The approach has been adopted in principle by all authorities regulating rice land suitability.

Piping water on-farm

Rice farms generally convey water around the property in open earth-lined channels and incur both seepage and evaporation losses of water as a result. Research into on-farm channel seepage losses has been performed on nine Riverina rice farms previously identified with seepage problems (Akbar and Khan 2005; Khan *et al*. 2007; Khan *et al*. 2005). The farms had a total of 32.2 km of unlined channels and 7.5 km of drains. Seepage losses were generally between 1 and 2%, with one farm losing 4% of allocated water due to particular soil conditions. For a large rice farm with a licensed allocation of 1400 ML, it was shown that combined losses could be > 60 ML/year – representing 4-5% of the farm's available water. Options to reduce these losses include lining or piping of channels, however there are significant practical limitations relating to the need to move large volumes of water and the energy costs of doing so. This attitude could change however with potential increase in water costs, and from this perspective is worthy of further consideration.

Piping water in the district, or lining supply channels

Over 42 GL/yr of water is lost from 500 km of channels as seepage, in addition to 12.5 GL/yr through evaporation from channel water (Akbar and Khan 2005). Seepage occurs primarily through "hot spots", ie where channels/drains cross coarse textured highly permeable materials. Potentially some

100 GL of water in the Murrumbidgee Irrigation Area and 105 GL in the Coleambally Irrigation Area (with potentially equivalent savings in the Murray Valley Irrigation Districts) can be saved each year through smarter and more integrated scheme to on-farm management. This represents roughly 16% of total water in these schemes so is a significant saving, however capital investment in improvements required to achieve these savings are large ($500-$4000 per ML water saved, depending on local conditions). (Akbar and Khan 2005;Khan *et al.* 2007; Khan *et al.* 2005)

Whole farm planning

Through currently available technology, electromagnetic surveys of whole-farm soil characteristics is possible. This has the potential to allow more efficient design of farm layouts to (for example) avoid inclusion of old stream-beds in rice bays, and hence to reduce drainage losses in irrigated rice production. Greater understanding of variation of soil type in a spatial sense also allows similar soil types to be grouped together in management zones, leading to increased efficiency in a range of processes from fertiliser utilisation to drainage of water.

The need for improved surface irrigation layouts that allow for the incorporation of the widest range of cropping options along with infrastructure (on farm drainage recycling facilities, investigated and evaluated soil suitability, large capacity supply and drainage facilities) to allow for large irrigation water volumes- and subsequently fast irrigation and drainage times are likely to be important adaptations – these strategies align with Land And Water Management Plans- but have been constrained in current adoption due to financial limitations during current drought conditions.

Raised beds in bays

Raised beds within irrigation bays has been suggested as a means of increasing water productivity in Riverina rice-based operations. In a north Queensland study in the 1990s, 32% water saving was demonstrated through the use of raised beds and saturated soil culture, over traditional flooding practice. No significant reduction in yield was recorded (Borrell *et al.* 1997). In more recent experiments in the Riverina, however, such water productivity benefits have not been demonstrable. High yielding rice crops can be successfully grown on raised beds, but when beds were ponded after panicle initiation for the required cold-temperature protection, there was no measured water saving compared with rice grown on a conventional flat layout (Beecher *et al.* 2006). The authors concluded that on Riverina rice-suitable soils, until ponded water is no longer required (for low temperature protection for current varieties, weed control etc), there is little scope for saving water while maintaining yield on suitable rice soil through the use of beds. The major difference with the study of Borrell *et al.* (1997) was the degree of permeability of the soils. The Queensland soil used in the experiments would not be classified as a rice-suitable soil under Riverina guidelines due to higher levels of internal drainage. With growing interest in aerobic rice cultivars which may be more suited to higher permeability soils (see section below on aerobic rice) raised beds may offer water productivity gains. There are likely to be increase flexibility and cropping.

Beds within terraced, bankless channel systems are being adopted in the Murrumbidgee Irrigation, Coleambally Irrigation, Murray Valley and by riparian and groundwater irrigators. A range of crops are being grown under variations of this style of layout including rice, wheat, maize, cotton, fababeans, chickpeas, barley, sunflowers. The area of adoption is not great at this stage but considerable attention is being focussed on to the performance of these commercial fields by other irrigators.

Surveyors and designers are generating and installing irrigation designs based on these concepts in the rice growing areas of southern New South Wales. Some growers are using relatively expensive designs in terms of structures and piping to achieve terraces/steps between bays in commercial situations but consider the labour saving benefits worthwhile. The ongoing adoption of terraced zero graded bankless channel rice layouts, including raised beds, appears likely given the increased cropping choice and flexibility and the significantly reduced labour requirement made possible by this type of layout. The adoption of these layouts will be constrained to locations where existing land grades allow creation of zero graded layouts with appropriate terrace widths (landforming costs not being excessive) and steps to allow adequate drainage and to where access to large irrigation flows are available in order to achieve satisfactory short duration water on/water off times for crops other than rice. There may be significant improvements to be made where pastures are grown in rotation with rice in flat layouts by increasing irrigation flow rates and reducing water on/ water off times.

The potential of these irrigation layouts fits with grower and grains industry desires to increase crop flexibility and yield potential e.g. crops after and in rotation with rice, fababeans, soybeans, canola, wheat, barley. The layouts would link to precision agriculture concepts – compaction control, tramlining, machinery efficiencies and uniform or varied input application.

Irrigation Scheduling

Water savings may be available from more efficient scheduling of irrigation for crops in rotation with rice. Irrigation scheduling aims to apply the required amount to the crop at critical times, and minimise losses through runoff and deep percolation, whilst maximising crop production. A study in California found that optimal irrigation required less (48-63%) water than what local growers referred to as ‘full’ irrigation. This also reduced both the deep percolation and runoff losses and caused a 31-43% increase in the application efficiency, and a 32-54% increase in net return (Raghuwanshi and Wallender 1998). There appears to be considerable scope within existing Australian irrigated rice-based farming systems to irrigate non-rice crops more efficiently and hence potentially divert more water for rice enterprises. This could include investment in more efficient irrigation technology (see below), in addition to more targeted application of irrigation water.

Combine and Sodsowing of rice

Combine and sodsowing of rice allows the possibility of delaying introduction of standing water, with the aim of reducing water loss through evaporation and drainage (Tabbal *et al.* 2002). An ancillary benefit in Australian rice systems is a decreased risk of duck damage to the young crop compared with crops established by aerially-sowing into standing water. Water savings have been reported however further research is required to understand the process on a range of soil types. Drilling rice presents problems in the heavy clay sodic soils such as those in the Murray valley where drilled rice has difficulty breaking through drying surface layers, due to the rice plant’s weak emergence capacity.

Breeding

- *increased yields to increase WUE.*

Average field water productivity of the total NSW rice crop roughly doubled over the period 1980–2000 (Humphreys *et al.* 2006). This was largely due to increased yields from new cultivars, overcoming restraints due to cold temperature damage, weed control, higher N rates, landforming etc, and water use savings from industry-regulated restrictions on allowable rice soils. The rice industry in Australia continues to invest in cultivar development to deliver increased yields from less water as a means of increasing water productivity further.

- *Varieties to reduce ponded evaporation*

Simpson et al (1992) found that for evapotranspiration from aerially-sown rice, 40% on average is due to evaporation from the ponded water surface, and the remaining 60% from the rice plants themselves. Early in the season all of the loss was evaporation from the water surface. In mid-December two thirds was via the plants, increasing to 90% in mid-January. It has been suggested that development of new varieties with optimum sowing dates which move ponded periods outside peak evaporation periods may represent another option for incremental gains in water productivity (Humphreys *et al.* 2005).

- *shorter season varieties*

Water use in ponded rice culture can potentially be reduced by the development of varieties with shorter crop duration (up to 10%)(Reinke *et al.* 1994), however there is some evidence that shorter durations will also result in less yield and hence reduced WUE (Williams *et al.* 1999). The length of the vegetative period is reduced for short-season varieties, thus limiting the time for sufficient biomass production to support high yield. Provided there are no limitations to growth during the foreshortened vegetative phase, short-season types have been shown to have similar yield potential to current long-season types. In recent times, however, by focusing on seedling vigour and early growth shorter duration varieties with high yield potential have been developed (Reinke *et al.* 2004). An associated benefit of shorter season rice varieties from a farming systems perspective is that they may facilitate earlier establishment of following winter crops, hence leading to higher yields and better system WUE (Humphreys *et al.* 2005). Continuing development of shorter season, higher WUE conventionally-irrigated rice cultivars is warranted, however significant industry interest in the Riverina is currently focussed on breeding and selection of aerobic and alternate wet-and-dry cultivars for the longer term (see section below) as a response to climate change in the region.

Increasing on-farm WUE by modifying farming systems

Aerobic and AWD rice

It has been suggested there is limited scope for further significant increase in irrigation or input water productivity through reduction in water use in current rice farming systems in Australia, and future savings must come from changing to alternative, lower water use practices, which are currently under investigation (Humphreys *et al.* 2006).

These include the potential for aerobic rice culture in Australia. There is published evidence from overseas that aerobic rice culture has the potential to increase water productivity over conventionally-irrigated rice – by 32–88% (Bouman *et al.* 2007; Bouman *et al.* 2005). Water losses are constrained by treating the rice like any other irrigated crop such as wheat or maize – once soil moisture has decreased to a specified level irrigation is then applied to bring the soil moisture content in the root zone up to field capacity. Ideally, the amount of irrigation required should match the evaporation from the soil surface and transpiration from the crop. The potential water-use reduction at the paddock level is large, especially in soils with higher drainage rates. In addition to drainage below the root zone declining, the concept is that evaporation decreases since there is no free water surface. Research in Australia on intermittent watering using existing rice cultivars showed that saturating the rice root zone with flooding every 7 days throughout the season reduced water use by 60%, but the negative effect on yields was dramatic (1–2 t/ha compared with 9 t/ha for conventional ponded culture) (Heenan and Thompson 1984). Grain quality was also negatively affected.

Experiments were also performed in the Riverina with sprinkler irrigation (Humphreys *et al.* 1989) and although water-use was reduced by 30-70%, yields declined by an even larger amount, resulting in decreased water productivity. These past experiences in Australia suggest a critical issue when considered alongside more positive reports (Bouman *et al.* 2005) is the importance of cultivars selected for their aerobic potential. Ideal aerobic rice cultivars combine the drought-resistant characteristics of upland varieties with the high-yielding characteristics of irrigated varieties (Lafitte *et al.* 2002). Chinese breeders have produced aerobic rice varieties with an estimated yield potential of 6–7 t ha. There are currently steps underway to trial some of these varieties in Australian conditions.

A major issue which will affect success of new aerobic rice cultivars in Riverina growing conditions is tolerance to low temperatures during microspore. As previously discussed, Australian varieties are protected from this risk by a water depth to 20cm. Such an option is not available in aerobic rice culture, and the reliance must come back onto genetic tolerance. It is possible that the best suited soils to aerobic rice production in Australia are the more freely draining soils currently not suitable for rice under ponded culture (due to high drainage losses). If this is the case, then another potential method of addressing the cold temperature constraints in the Riverina is to relocate aerobic rice production further north to warmer climatic conditions hence mitigating low temperature risk.

Another outstanding issue for aerobic rice in the Riverina is weed control. In addition to providing water supply and low temperature protection to irrigated rice, it would be expected that aerobic rice would require conventional weed control and hence result in increased chemicals in these systems.

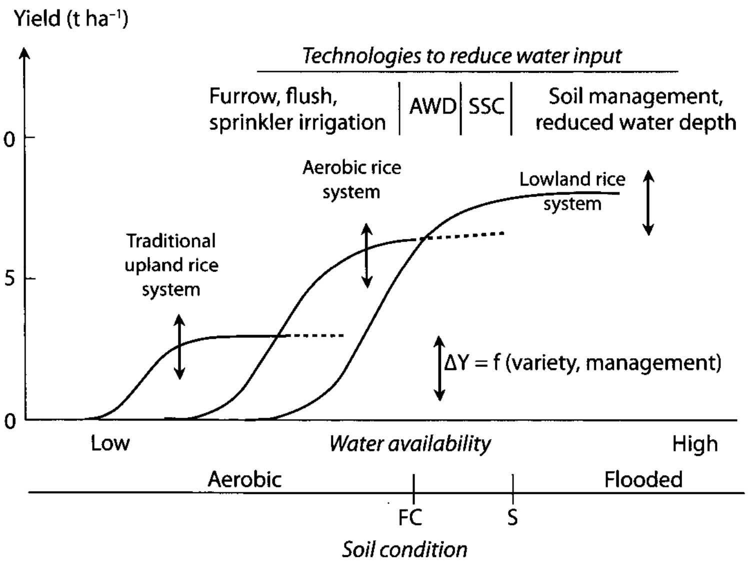


Figure 4.10: Schematic presentation of yield responses to water availability and soil conditions in different rice production systems and their respective technologies to reduce water inputs. (Bouman et al. 2007). AWD = alternate wetting and drying, SSC = saturated soil culture, FC = field capacity, S = saturation point, ΔY = change in yield.

AWD refers to *alternate wet and dry* culture, also aimed at reducing evaporation and deep drainage losses, but not to the extent of aerobic rice. For current Australian rice varieties, there is no yield loss with intermittent irrigation for the first 10–11 weeks, offering the opportunity to save irrigation water and increase water productivity immediately (Humphreys 2006). Following the intermittent irrigation phase management proceeds as for normal irrigated rice, providing the low temperature protection with increased water depth at the critical stage. Water use saving of 10-15% may be possible for no appreciable loss in yield. Saturated soil culture (SSC) or very shallow water (Bouman and Tuong 2001) is another option, reducing hydraulic head, drainage losses, and there is evidence that it can increase water productivity. Figure 4.10 clearly shows a succession of options for reducing water use in rice production systems and general consequent trends in yield.

In summary the AWD technology presents the most immediate option for the Australian situation, although it offers only modest increases in water productivity and limits rice production to existing rice-suitable soils. Aerobic culture offers the promise of significantly enhanced water productivity benefits, together with the potential for expansion in geographical range of production. There is a need for further research into suitability of existing international aerobic cultivars for Australian conditions and variety of soils, including issues relating to water productivity, irrigation and fertiliser management, weed control, and low temperature sensitivity.

New farm layouts

A potential strategy is to intensively irrigate a smaller area of the farm as close as possible to the water supply source, and consider the remainder dryland, thereby minimising losses from channel conveyancing systems. This may work best in conjunction with new irrigation technologies (see below). Similarly the lowest percolation soils could be selected for an intensive rice rotation in lasered terraces best suited to rice with separate new layouts used for non rice rotations.

Investment in more efficient irrigation technology

With increasing pressure on decreasing water supplies, and likelihood of increased variability, some growers are now considering investment in more water efficient irrigation methods (pressurised systems, lateral move, centre pivot, subsurface drip)as a means of watering non-rice crops on lighter-textured soil. Water savings benefits from more efficient irrigation technology in the Riverina range between 16-35% for cereals, 15% for soybeans, and 7% for maize (Khan *et al*, 2005). Lateral move systems cost roughly $1500/ha, and centre-pivot systems $2000-$2500/ha (Khan *et al.* 2005). Centre-pivot and lateral move irrigation systems have low labour requirements (Raine and Foley 2002), which needs to be accounted for in any economic analysis. All these systems require considerable initial investment and the cost-benefits are largely unknown, representing a major research need in the Riverina irrigation districts, particularly as a function of soil type, climate-change scenario, water pricing scenarios, and crop price scenarios. Obviously, pressurised irrigation systems are not an option for existing rice growing systems, however on non-rice areas of the farm (lighter soils) represent an option for increasing water productivity and hence could influence rice production via affect on available water.

New crops, rotations and priorities for water

With climate change projections suggesting a future reduced and more variable water supply, some Riverina irrigators are questioning previous priorities for water and asking questions like:

- what do optimal irrigation water priorities look like if my farm is no longer to be a fully-irrigated enterprise? Is it better to partially-irrigate everything or plan to intensively irrigate a small portion of the farm with the remainder dryland?
- how does a small intensively irrigated area of vegetables, maybe under a sub-surface drip irrigation system compare with conventional rice production?
- how would aerobic rice (if found to be viable) affect water priorities on farm, and impact on other crops, rotations, weed control, diseases etc.
- with reduced water, what is the optimal combination of livestock and cropping
- is water better diverted to winter crops as first priority due to their need for supplemental irrigation only, and should rice be considered an option only in years with high allocation.
- how would alternative rice production systems (aerobic & AWD) affect the water equation

These are all very valid questions for which there is an absence of research answers at present, particularly under a changing climate.

Risks of Maladaptation

- The water saving possibilities with aerobic rice culture could lead to increased problems with cold damage, nitrogen loss and weeds, with potentially more chemicals in the environment, and accumulation of salt in the root zone. Conventionally irrigated rice results in a net movement of salt down through the profile, and is thus an important tool for managing salinity

- Piping of water increases efficiency and reduces water loses, but could have significant negative effects on biodiversity, native vegetation, and could potentially increase water demand of other crops which benefited from the seepage.

- Reduced areas of irrigated rice culture may have negative biodiversity consequences on-farm (Doody *et al.* 2004).

- Increased N fertilisation in response to higher CO2 could have negative greenhouse gas implications

- Life cycle analyses (ie breakdown of materials) of piping as greenhouse gases associated with these

- Large investments by irrigated industries in infrastructure costs, new irrigation technologies and equipment is setting the scene for even greater losses if the current situation of no water continues

- Increased water infrastructure costs may not offset water losses

Costs and Benefits

AWD Rice Culture

The costs of implementing AWD culture is minimal as no new infrastructure is required, and 10-15% savings are potentially available.

Piping/lining channels

Capital investment in improvements required to achieve these savings are large ($500-$4000 per ML water saved, depending on local conditions)(Khan *et al.* 2007; Khan *et al.* 2005). In view of potential earnings from irrigation water from rice and wheat (105 and 75 $/Ml respectively), a pay-back period in the range of 6 – 53 years is estimated.

Investment in more efficient irrigation technology

Lateral move systems cost roughly $1500/ha, and centre-pivot systems $2000-$2500/ha (Khan *et al.* 2005). Potential benefits are likely to depend heavily on soil type, enterprise mix, water and commodity process, and irrigators considering investments of this type feel they do not have access to enough information on these. This represents an urgent knowledge gap in adaptation of Riverina irrigated farming systems.

Knowledge Gaps and Priorities

What will be the impact of climate change on allocations in the Riverina?

A more updated assessment on sustainable irrigation water allocations under climate change is expected from the CSIRO Land & Water "Murray Darling Basin Sustainable Yields Project" which is due to report to the National Water Commission by the end of 2007. This project will assess a range of projected future climate scenarios (using the 4th IPCC archived modelling results for 15 GCMs) and potential future development scenarios (farm dams, surface and groundwater extractions, commercial plantations, domestic requirements etc) for all major catchments within the Murray Darling Basin, and report on surface water and ground water availability impacts both in terms of average yields but also variability

Use of Seasonal Climate Forecasts

With projected increases in water supply variability, there is a growing need for effective and targeted seasonal climate forecasting to assist in early planning of farm operations from expectations of the coming season's water supply and demand. Limited research has been conducted into how this information should best be used in irrigated farming system management, yet potential benefits are large.

Aerobic and AWD Rice in Australia

There is evidence that aerobic rice represents an option to increase water productivity whilst maintaining production of rice which supports numerous regional towns and industries in the Riverina. There are numerous unknowns:

- Regional and physical applicability of aerobic rice,
- Potential impact on water productivity as a function of soil type and region.
- Optimal irrigation, weed control and fertilisation strategies
- Potential of internationally-available aerobic rice cultivars with cold tolerance to allow the shift away from the current irrigated rice system in Australia.
- Most important traits associated with adaptation to aerobic conditions in Australia – an understanding of these is critical to facilitate potential further breeding efforts.

Cost-benefits of investment in more efficient irrigation technologies

Growers throughout the Riverina need to include cost-benefit analysis of investment in efficient irrigation technologies into their planning for the future, however there is a real and significant lack of understanding relating to the water productivity gains achievable from investment in different irrigation technologies (lateral move, centre pivot, subsurface drip) under a changing climate (Sam North, NSW DPI, Deniliquin, *pers comms*). These gains are likely to vary greatly as a function of soil type, potential future water pricing, commodity prices etc.

Better water productivity from new farming systems

Rice farmers are involved in a wide range of agricultural industries in addition to rice. In a future with projected reductions in average water supply, increased demand, and a likelihood of increased variability of supply, there is a lack of knowledge in both the farming and research communities on how current farming systems compare with a wide range of potential modified systems. Questions needing to be answered include:

- What might the optimal rotations and farm layouts look like with less water in a changed climate?
- At what point in terms of allocation reductions does it become uneconomic to maintain the existing bays and surface irrigation infrastructure?
- Does potential investment in new irrigation technology change the picture for optimum enterprise mixes under a changed climate?

These are only a small selection of whole-of-farm scale questions which need urgent research attention from the perspective of adapting irrigated farming systems in the Riverina to climatic change.

Catchment Issues

A better understanding is needed of how water savings on farm effect water demand in other areas of the catchment (ie whole-of-catchment modelling of adaptation scenarios)

Table 4.2: Summary of climate change adaptation options for the rice industry indicating whether the option 1) has already been assessed or is a remaining knowledge gap, 2) is highly feasible, 3) would be feasible / effective immediately, or 4) should be a high priority for research, assessment and implementation in developing adaptation strategies.

Adaptation options	**Options already assessed**	**Options with high feasibility**	**Immediacy**	**Priority activities**
Policy level				
Develop linkages to existing government policies and initiatives e.g. GGAP, Greenhouse challenge, salinity, water quality, rural restructuring	✓	✓	✓	✓
Ensure communication of broader climate change information	✓	✓	✓	✓
Maintenance of effective climate data distribution and analysis systems	✓	✓	✓	✓
Modification of existing Federal and State Drought policies to encourage adaptation	X	X	✓	✓
Continue training to improve self-reliance and to provide knowledge base for adapting	X	✓	✓	✓
Policy settings that encourage development of effective water-trading systems that allow for climate variability and support development of related information networks	✓	✓	✓	✓
Public sector support for a vigorous agricultural research and breeding effort with access to global gene pools	✓	✓	✓	✓
Maintain R&D capacity, undertake further adaptation studies which include costs/benefits and streamline rapid R&D responses	✓	✓	✓	✓
Develop further crop systems modelling capabilities such as APSIM and quantitative approaches to risk management	✓	✓	X	✓
Encourage appropriate industry structures to enable flexibility	?	?	?	?
Encourage diversification of farm enterprises	✓	X	X	✓
Ensure support during transition periods caused by climate change and assist new industry establishment	X	✓	X	✓
Altering transport and market infrastructure to support altered production regimes caused by climate change	X	✓	X	X
Encourage financial institutions to be responsive to changing industry needs	?	?	?	✓
Continuing commitment from all levels of government for pest, disease and weed control	✓	✓	✓	✓

Adaptation options	**Options already assessed**	**Options with high feasibility**	**Immediacy**	**Priority activities**
including border protection				
Introduction of climate change adaptation into Environmental Management Systems	✓	✓	✓	✓
Crop and farm management				
Establish new higher water productivity farming systems (potentially including aerobic & AWD rice)	?	?	?	✓
Investment in more efficient irrigation technology	?	?	?	✓
Improved farm plans and layouts	?	?	?	✓
Development of participatory research approaches to assist pro-active decision making on-farm	?	✓	✓	✓
Develop further risk amelioration approaches (e.g. zero tillage and other minimum disturbance techniques, retaining residue, extending fallows, row spacing, planting density, staggering planting times, erosion control infrastructure)	✓	✓	✓	✓
Develop further controlled traffic approaches – even all-weather traffic	✓	✓	✓	✓
Research and revise soil fertility management (fertilizer application, type and timing, increase legume phase in rotations) on an ongoing basis	✓	✓	✓	✓
Alter planting rules to be more opportunistic depending on environmental condition (e.g. soil moisture), climate (e.g. frost risk) and markets	✓	✓	✓	✓
Expand routine record keeping of weather, production, degradation, pest and diseases, weed invasion	X	✓	✓	✓
Tools and extension to enable farmers to access climate data and interpret the data in relation to their crop records and analyse alternative management options.	X	✓	✓	✓
Climate information and use				
Improve dynamic climate modelling tailored towards decision making in agriculture	?	?	?	✓
Incorporate seasonal forecasts and climate change into farm enterprise plans so as to be able to readily adapt	?	?	?	✓
Maximise utility of forecasts by RD&E on combining them with on-ground measurements (i.e. soil moisture, nitrogen), market information and systems modelling.	?	?	?	✓
Warnings prior to planting of likelihood of very hot days and high erosion potential	?	?	?	✓

Adaptation options	**Options already assessed**	**Options with high feasibility**	**Immediacy**	**Priority activities**
Water resource issues				
Further improvements in water distribution systems (to reduce leakage and evaporation), irrigation practices such as water application methods, irrigation scheduling and moisture monitoring to increase efficiency of use	✓	X	X	✓
Maintain access rights to water	✓	?	✓	?
Develop water trading system (and associated information base) that can help buffer increased variability	✓	✓	✓	X
Maximise water capture and storage on-farm – needs R&D and policy support	?	?	X	✓
Managing pests, disease and weeds				
Improve pest predictive tools and indicators	✓	✓	✓	✓
Improve quantitative modeling of individual pests to identify most appropriate time to introduce controls	X	✓	X	X
Further development of Area-wide Management operations	✓	X	✓	?
Further development of Integrated Pest Management	✓	✓	✓	?
Improved monitoring and responses to emerging pest, disease and weed issues	✓	✓	✓	X
Crop breeding				
Selection of varieties with appropriate thermal time and vernalisation requirements, heat shock resistance, drought tolerance (i.e. Staygreen), high protein levels, resistance to new pest and diseases and perhaps that set flowers in hot/windy conditions	?	✓	?	✓
Ongoing evaluation of cultivar/management/climate relationships	?	✓	✓	✓
Land use				
Potential for cotton, summer-growing grains and pulses further south	?	?	?	✓
Movement to more livestock in the enterprise mix	?	?	?	✓

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5: SUGARCANE

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Key Messages:

- Probably the greatest impact (and adaptation challenge) for the Australian sugarcane industry will be the projected change in the amount, frequency and intensity of future rainfall. In many regions the amount of effective rainfall available to the crop will be reduced, whilst demand is likely to increase due to greater rates of evapotranspiration linked to atmospheric warming.
- A range of adaptation strategies are needed across the entire sugar cane industry value chain in the coming years if it is remain sustainable under a changing climate. Strategies must be tailored to individual regions to take account of differences in biophysical and logistical characteristics.
- Adaptation options available to the sugarcane industry can be categorised into those seeking to: improve the management of limited water supplies; technological fixes based on reductionist analysis; engineering design principles, or computer-aided models; altered cropping system design and agronomic management (typically requiring changes in attitudes and behaviour); decision making tools (including the use of climate forecasting and information sources); and institutional change.
- This chapter has detailed numerous knowledge gaps and priority areas for research, development and extension (R,D&E). These include: improvements to farming practice; development of innovative farming and processing systems that take an integrated and sustainable approach to risk and opportunity across all inputs; capitalisation of bio-energy opportunities and carbon trading potential for value adding; greater focus on sugarcane physiology and plant improvement in varietal characteristics; enhancing human capital through building skills and enhancing science capability in climate understanding and risk management; the linking of biosecurity management to a changing climate; and a greater understanding of the global context of climate change impacts on worldwide production, profitability and markets relative to the Australian sugar industry.
- Many of the knowledge gaps detailed above can be best filled through the enhancement of existing R,D&E activities. Other knowledge gaps are either related to projection uncertainty and impacts of future climate variability, or sugarcane physiology.
- Building social capital through targeted extension, improving skills and providing a more industry-wide knowledge base are all essential for future adaptation. Additional knowledge gaps will undoubtedly come to light as the sugarcane industry responds to a changing climate.

Introduction

Sugarcane production in Australia is mainly focused in discontinuous regions spanning 2100 km of the coastal plains of eastern Australia, from Mossman in the Far North of Queensland, to Grafton, northern New South Wales (Figure 5.1). The majority of these regions are within 50 km of the coastline and in close proximity to tidal rivers and creeks. In 2006 production in Queensland occupied nearly 380,000 ha of land (Australian Sugar Milling Council, 2006). Queensland generally produces approximately 94% of the country's raw sugar production (CANEGROWERS, 2007). Northern New South Wales accounts for around 4% of production and a small area in Western Australia's Ord River Irrigation Area produces the remainder. Depending on prices, the industry generates between $1.5 - $2 billion in direct revenue, with approximately $1.2 billion from export markets (CANEGROWERS, 2007).

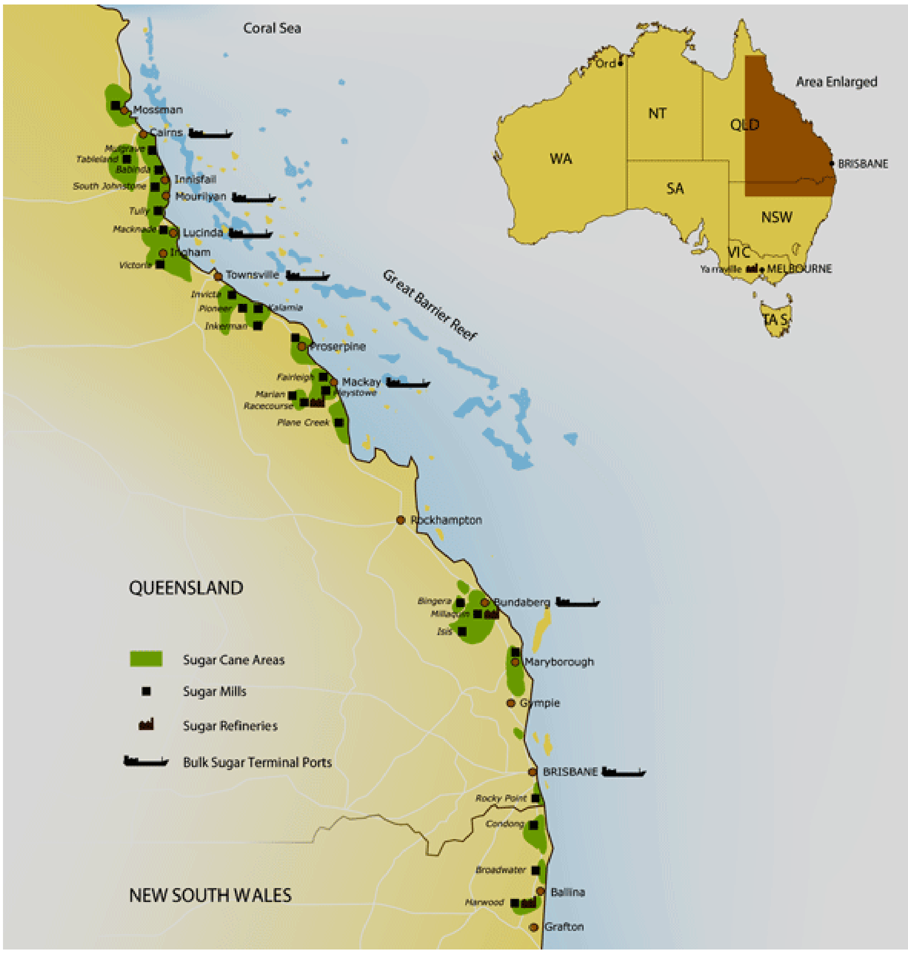

Figure 5.1: Sugarcane growing regions of the east coast of Australia. Source: CANEGROWERS website.

The sugarcane industry on the east coast of Australia can be categorised into four regions referred to as the Far North (Mossman in the north, south to Ingham), the Burdekin and Atherton Tablelands, the Central region (Proserpine south to Maryborough) and the remaining areas in south east Queensland and northern New South Wales. The four regions span a number of climatic zones, from the wet tropics in the north through to the dry tropics and humid sub-tropics in more southerly locations, and can be defined by 3 major climatic constraints to primary production; water availability, radiation and temperature.

Potential yield is limited in the Far North by an excess of summer rainfall (annual rainfall is approximately 3000 mm) and associated cloud cover and low levels of radiation. The Burdekin and Atherton Tablelands, although not geographically linked, are both distinct from other cane growing regions in that production is enhanced by an abundant supply of irrigation water from the Burdekin Dam and the Atherton Tableland water supply scheme, respectively. The production potential of the dry tropics of the Central region, although providing an ideal temperature for the growth of sugarcane, is constrained by a limited supply of irrigation and rainwater. Conversely, south east Queensland and northern New South Wales receive abundant rainfall for sugarcane production, but cool winter temperatures and low radiation levels result in slow growth rates.

Climate Change Impacts

Climate Change Projections

Many regions have already experienced changes in climate, including warming of minimum and maximum temperatures as well as changes in precipitation. Some of these changes can be directly attributed to global climate change, such as regional warming however recent changes in rainfall are far more difficult to attribute to this driver (CSIRO 2007). Whilst some uncertainty does exist as to the extent to which historical changes in climate can be attributed to global climate change it is clear that further changes are expected in the future.

CSIRO (2007) national projections of climate change particularly relevant to the present sugarcane production areas include:

- General trend towards a hotter and drier climate.
- Projected change in maximum and minimum temperatures resulting in a decrease in diurnal temperature range.
- Strong increase in the frequency of hot days and warm nights and a moderate decrease in frost.
- Little change in precipitation in the far north. Decreases in precipitation elsewhere (particularly in winter and spring months), with slight increases in summer and autumn.
- Increase in daily precipitation intensity and the number of dry days.
- Little change to annual solar radiation.
- Increase in annual potential evapotranspiration.
- Increase in agricultural droughts (i.e. changes in the seasonal temperatures and/or the distribution or amount of rainfall producing periods of extremely low soil moisture).
- Tendency for increased average wind speed in most coastal areas.
- Global average sea level rise of between 18 and 59 cm by 2100 (excluding any contribution from ice sheets) relative to 1990, with increases on the east coast of Australia possibly greater than the global mean. Sea level rise and increased wind speeds exacerbating storm surges and the inundation of low-lying coastal terrain.
- Increased number of intense tropical cyclones, but possible decrease in the total number of cyclones.
- Uncertain effect on El Niño Southern Oscillation (ENSO)

Projected temperature and precipitation changes can vary significantly at fine spatial scales, particularly in coastal areas (CSIRO, 2007). In order to capture this spatial variability point scale seasonal projections of temperature and rainfall change have been extracted for 11 sugarcane growing regions along Australia's east coast using the OZCLIM scenario generator developed by CSIRO Atmospheric Research and the International Global Change Institute (http://www.cmar.csiro.au/ozclim). Further details of the methodology used and projected changes for 2020 and 2030 can be found in the Appendix (Chapter 13).

Expected regional changes in temperature

Projections for 2020 suggest that minimum temperatures (Tmin) across the sugarcane regions of Queensland will increase between 0.3 ^{o}C (low emission scenario) and 1.1 ^{o}C (high emission scenario) relative to the mean baseline period of 1961 to 1990. Maximum temperatures (Tmax) are projected to increase by a similar extent.

By 2030 minimum temperatures are projected to increase by 0.4 ^{o}C (low emission scenario) to 1.6 ^{o}C (high emission scenario) with similar increases in maximum temperatures. The similar rates of projected change in maximum and minimum temperatures are at odds with current observations showing a 32% faster rate of warming in Australia's minimum temperatures (CSIRO 2007)

Expected regional changes in precipitation

Scenarios generated using the DARLAM125 climate model indicate that by 2020 a slight increase (up to 4.2%) in autumn and winter rainfall is likely to occur. This increase will be offset by reductions in both summer and spring rainfall (up to 2.5%). By 2030 continued increases in autumn and winter rainfall are projected (up to 6.4%) and continued declines in spring and summer rainfall (as much as 3.6%).

Scenarios generated using the HADCM3 model suggest likely reductions in annual rainfall of between 5 to 7% by 2020 and up to 10% by 2030.

Impacts

A number of primary and secondary impacts are expected in response to warming and rainfall change. Table 5.1 provides a summary of possible impacts of climate change on sugarcane production in Australia on the grower, harvest, transport and milling sectors. This information has been drawn from physiological data for sugarcane and other crop species (with an emphasis on other C_4 grass species), climate change literature and consultation with industry stakeholders at regional workshops. Climate change is likely to have both direct and indirect impacts on sugarcane production. Table 5.1 provides an overview of possible direct impacts at the field scale and the immediate management of the cropping cycle.

Table 5.1: Summary of possible impacts of climate change and potential adaptation strategies on the grower, harvester, transport and milling sectors of the sugar industry in Queensland (adapted from Park *et al.* 2007*c*).

Sector	Likely impact	Potential adaptation strategies
Grower	1. Increase in atmospheric CO_2	
	a. Increased crop biomass (through CO_2 fertilisation resulting in an increase in water use efficiency (WUE), and stalk growth, diameter and tillering).	a. Optimise availability of all necessary resources to the crop.
	b. Increased abundance and competitiveness of weeds (particularly those with a C_3 photosynthetic pathway). Could lead to an increased resistance to glyphosate.	b. Use transgenic cultivars, biocontrol agents, cultural practices and expert systems for improved weed management.
	c. Increased partitioning to vegetative matter (i.e. increased volume of trash).	c. Increased capacity for weed suppression in trash blanketed systems.
	d. Higher C:N ratio of leaves (i.e. reduced leaf N concentration) resulting in slower rates of decomposition and greater immobilisation of soil N stores, and impact on photosynthetic capacity.	d. Improved management of N inputs at sowing and during growth.
	e. Higher C:N ratio of leaves resulting in altered leaf palatability for sucking insects and pathogenic fungi (with possibly compensatory pest feeding in response to low N concentrations in leaves and cane.	e. Increased integrated pest management.
	2. Increase in temperature	
	a. Increased yield as a result of accelerated phenology reducing the time to crop maturity and maximum sucrose content, increased rate of canopy development, extended growing season due to increase in minimum temperatures, less restrictions on growth in presently cool locations.	a. In growth-constrained regions, revise the cropping cycle to either grow crops for a longer period of time to increase yield, grow crops for shorter periods to maintain current yields and enable additional fallow or cash crops to be included in the cropping cycle, or plant crops earlier in the season to coincide with cooler seasonal temperatures. In high input regions already experiencing excessive stalk growth rates and lodging (e.g. Burdekin), manage for shorter crops and reduced biomass accumulation by planting later and emphasising erect growth habit in breeding and variety selection.
	b. Decreased yields as a result of increased vapour pressure deficit, stomatal closure and leaf damage resulting from high temperatures.	b. Use varieties with greater tolerance to higher temperatures.

Sector	Likely impact	Potential adaptation strategies
	c. Decrease in sucrose content (as a result of higher temperatures during the harvest season).	c. Optimise availability of all necessary resources, alter the duration of the harvest season to coincide with cooler temperatures, use varieties (or management practices, i.e. irrigation scheduling) to limit expansive growth in favour of sucrose accumulation, use ripeners to better manage sugar accumulation.
	d. Increased incidence of pests and diseases, either through increased survival of populations through the winter periods, the spread of exotic populations into more extensive climatic windows, and altered ecological interactions with natural enemies.	d. Use cultural practices (e.g. strategic tillage, use of legume crops to break soil pest and disease cycles), insecticides, fungal and bacterial biopesticides, varieties with improved resistance, integrated pest management, decision support software, revision of quarantine boundaries and consideration of pest strategies presently used by more northerly regions.
	e. Increased C decomposition and soil N mineralisation may occur under changed temperature and rainfall conditions (stimulating net primary production) resulting in a change in the C:N ratio of the soil.	e. Review best management practice with regard to soil C and N management, (may include the use of precision agriculture and legume crops to boost soil organic C and N stores).
	f. Increased partitioning into trash and fibre (at the expense of sucrose storage in the cane stalk).	f. Where sugar is the focus of production, use varieties with low vegetative growth habits and stalk fibre content, and cultural practices to reduce vegetative growth (e.g. irrigation).
	g. Altered flowering propensity and regimes affecting in-field breeding programmes.	g. Management of crop development using controlled temperature facilities.
	h. Poleward shift in climatic zones suitable for sugarcane production.	h. Relocation of sugarcane production (taking into account present milling capacity and location, supporting infrastructure and competing land uses).
	i. Impacts on CCS of warmer autumn and winter temperatures and changes in the diurnal temperature range.	i. Use varieties suited to altered climatic conditions.
	3. Decrease in rainfall	

Sector	Likely impact	Potential adaptation strategies
	a. In moisture limited regions, decreasing yields as a result of increased crop water stress (through decreased availability of soil moisture and supplementary water supply), decreased quality of supplementary water, increased solar radiation and evaporation through reduced cloud cover, reduced rate of early leaf area and canopy development through water stress, reduced photosynthesis, decreased tillering and stalk length, and increased cost of production as a result of increased use of irrigation water and the exacerbation of soil salinity and rising water tables.	a. Introduction of irrigation technology, increased use of supplementary water through irrigation, optimisation of irrigation scheduling to maximise WUE, use of more effective irrigation water delivery technologies (i.e. trickle tape), construction of on-farm water storage facilities, laser levelling to direct excess surface water to storage facilities, use of drought-tolerant or more water efficient varieties, modification to row spacing, minimum tillage and the use of cover crops.
	b. Excess water regions = increased yields as a result of decreased water-logging and flooding events, increased solar radiation through reduced cloud cover, decreased nutrient loss through erosion, potential increased CCS through a more effective drying-off period, increased trafficability for harvest machinery.	b. Optimise availability of all resources (possibly through precision agriculture).
	4. Increase in rainfall intensity	
	a. Increased offsite movement of nutrients and sediment.	a. Use of trash blanketing to intercept raindrops, inhibit lateral movement of water, reduce evaporation, and improve soil structure and water infiltration through retention of trash blanket to increased soil C stores, use of conservation tillage to reduce soil compaction, and the use of drainage ditches and laser levelling to control localised flooding and retention of surface water, nutrients and sediment.
	b. Decreased yield through reduced infiltration of rainfall into the soil.	b. Use trash blanketing to intercept raindrops and increase water infiltration; conservation tillage to reduce soil compaction, and alterations to row configurations.
	5. Rise in sea level	
	a. Increased flooding, land degradation, and damage to infrastructure.	a. Construction of man-made seawater defences, and relocation of the cane industry.
	b. Exacerbation of storm and cyclone damage.	b. Construction of man-made seawater defences, and relocation of cane industry.
	c. Increased intrusion of saltwater into coastal aquifers impacting on the quality and quantity of coastal fresh water supplies.	c. Restrictions on groundwater pumping and construction of new bores, abandonment of bores already impacted by saltwater intrusion, ongoing monitoring of water quality.
	6. Increase in cyclone intensity	

Sector	Likely impact	Potential adaptation strategies
	a. Physical damage to crops (including leaf pruning, lodging and complete unearthing) and infrastructure.	a. Plant trees around the paddock to act as a windbreak, use harvesting machinery suitable for harvesting a lodged crop, varieties with reduced propensity to lodging and cultural practices to reduce lodging (e.g. hilling up), diversify into crops with a shorter duration, and utilise insurance and re-insurance options to offset risk
Harvest	a. Change in yield and increase in trash volume.	a. Use appropriate harvester technologies and cutting rate.
	b. Change in the time of crop maturity and harvesting.	b. Use seasonal climate forecasts to help plan harvesting and optimisation decision-making tools to aid rostering of harvests and labour and equipment resources.
	c. Excess water areas - decreased rainfall as a result of improved harvester efficiency (less slippage of harvester and haul-out machinery) and reduced stool and paddock damage.	c. Utilise optimisation decision-making tools to aid rostering of harvests and seasonal climate forecasts to aid the planning of labour and equipment.
	d. Decreased yield as a result of increased lodging from cyclone and storm events.	d. Use appropriate harvester technologies and cutting rate, decrease capital stock in proportion to reductions in crop yield.
Transport	a. Increased damage to infrastructure (especially coastal highways and railways) as a result of an increased number and intensity of extreme events.	a. Construction of man-made seawater defences, relocation of cane industry.
	b. Change in yield volume and the addition of other crop species into the cropping cycle.	b. Utilisation of existing transport capacity and additional road networks to transport cane and other crop species, decrease capital stock in proportion to reductions in sugarcane yield.
Milling	a. Increased damage to mill infrastructure as a result of an increased number and intensity of extreme events.	a. Construction of man-made seawater defences, relocation of cane industry.
	b. Alteration in the timing and duration of the crushing season.	b. Use seasonal climate forecasts to help plan optimum harvesting and crushing season.
	c. Decrease in yields resulting in the reduced financial viability of the mill.	c. Excess mill capacity utilised by diversifying into additional crop species (e.g. sorghum), optimise crushing rate.
	d. Deceleration of mill processing, suppression of sucrose extraction, increased wear and tear on infrastructure and increased volumes of mill mud for disposal as a result of an increased volume of extraneous matter contained in the cane consignment due to increased lodging.	d. Utilise advances in mill technology including improved clarifier design and modified mud scrapers.

In order to consider the climate change impacts on the sugarcane industry, is it important to understand the integrated nature of the value chain. In some cases, a positive impact in one sector may result in a negative impact elsewhere in the value chain. For example, an extended harvest season may be a positive impact for the harvesting, transport and milling sectors since it would reduce the requirement for capital stock (harvesters, trucks, etc), but it may be negative for the growing sector since a greater proportion of the crop may be required to be harvested at a time of year when CCS levels are less than optimal. Individual climate change variables have been considered in a value chain context for the Maryborough mill region (Park e*t al.* 2007*b*). In this study, the adaptive responses to primary impacts of climate change are considered throughout the value chain, and secondary and subsequent impacts and response strategies assessed in a meaningful whole of industry context. Maryborough mill region has been used in this example as it is typical of many of the sugarcane-producing regions on the east coast of Australia, in that it is close to the coast and tidal waterways, it contains areas of low-lying production and predominantly relies on rainfed production.

The impacts detailed in Table 5.1 above do not explicitly take into account institutional and biophysical differences between the sugar-growing regions in Australia. Regional variations imply that the magnitude of impacts (and opportunities) on each region will vary with geographic location. In order to illustrate more regionally-specific impacts, Table 5.2 provides a summary of the present constraints to production in 5 cane-growing regions and the likely impacts of climate change on these.

Table 5.2: Summary of potential climate change related impacts on sugarcane production regions on the eastern coast of Australia (adapted from Park *et al.* 2007*a*).

Region	Present or potential future constraints	Likely impact of climate change
Northern	Low radiation experienced when cloudy.	Constraint likely to be unchanged by limited changes in radiation, but may increase as rainfall reduces.
	Damage to the crop (and subsequent ratoon crops) during cyclone events.	Increased damage to crop (and subsequent ratoon crops) with an increase in cyclone intensity.
	Excess of water (rainfall and regional flooding) during the wet season leading to waterlogged paddocks and limited access for operations including harvesting.	Whilst there is projected to be only small changes in rainfall in the near future, reductions in rainfall by the middle of the century will reduce the extent and frequency of waterlogging and improve the timeliness of in-field operations. Any increase in autumn and winter rainfall may shorten duration of harvest season and increase the need for greater mill capacity, and delay seasonal increases in CCS (and the start of the harvest period).
	Offsite movement of nutrients, chemicals and sediments to the Great Barrier Reef Marine Park.	Likely to increase with the projected increase in the intensity of rainfall and cyclone events.
	Poor crop establishment.	Projected reduction in spring rainfall may inhibit establishment.
	Poor drainage.	Likely to be exacerbated by projections of sea level rise and rainfall intensity.
Herbert / Burdekin	Security of water supply in the Burdekin region.	Likely to experience increasing competition for water from the Burdekin Dam due to (a) reduced quantity and effectiveness of rainfall (increased runoff resulting from increased rainfall intensity), and (b) human population growth and industrial expansion of the Townsville - Bowen region.
	Rising water table and salinity issues in the Burdekin River Irrigation Area	Likely to increase with increased use of irrigation under hotter temperatures and reduced rainfall, increased evapotranspiration, especially in the absence of improvements in water use efficiency and irrigation scheduling.
	Rising saline groundwater table (Burdekin) and poor drainage (Herbert and lower Burdekin)	Likely to be exacerbated by projected sea level rise and potential intrusion into the ground water.
	Catchment hydrology and water availability (Burdekin floodplain).	Reductions in rainfall will reduce the recharge rate into the Burdekin aquifer.
	Poor harvesting efficiency.	Projected reduction in winter and spring rainfall are likely to increase the efficiency of harvesting operations, increased cyclone intensity may increase lodging and reduce harvesting efficiency.

Region	Present or potential future constraints	Likely impact of climate change
	Offsite movement of chemicals, nutrients and sediments to the Great Barrier Reef Marine Park.	Likely to increase with an increase in the intensity of rainfall and cyclone events.
	Tidal intrusion in the Herbert and lower Burdekin deltas.	Likely to be exacerbated by projected sea level rise.
Central	Limited supply of irrigation water.	Likely to be exacerbated by projected reduction in rainfall, increase in rainfall intensity (reduced infiltration) and the number of dry days, increase in evapotranspiration and agricultural droughts.
	Limits to crop growth in the frost-prone areas in the western districts.	Projections of an increase in minimum temperatures and decreased frost likely to decrease limits to crop growth.
	Offsite movement of chemicals, nutrients and sediments to the Great Barrier Reef Marine Park.	Likely to increase with the projected increase in the intensity of rainfall and cyclone events.
	Variable annual yields	Projected increase in temperatures likely to extend the growing season with the potential of increased productivity and reduced impact from variable yields (providing all other inputs are unlimited – see 'Limited supply of irrigation water' above).
	Poor drainage and tidal intrusion in the lower floodplains.	Likely to be exacerbated by projected sea level rise.
Southern	Limited supply of irrigation water	Likely to be exacerbated by the projected decrease in rainfall.
	Crop growth limited by low winter temperatures and short duration of growing season.	Projected increase in minimum temperatures likely to reduce constraint with a potentially increase productivity (providing all other inputs are not limited).
	Present competition for land-use from other crops *e.g.* horticulture and tree crops.	Competition may increase due to the relatively greater risk of growing a 4-5 year sugarcane crop given projections of increased extreme climate events, compared with short-duration annual crops.
NSW	Low levels of solar radiation constrain crop growth	Projections of a decrease in rainfall and associated cloud cover likely to reduce constraint.
	Production is prone to frost damage	Projections of an increase in minimum temperatures and a reduction in frost are likely to decrease constraint.
	Crop growth presently limited by low winter temperatures and short duration of growing season (necessitating a crop duration of 2 years)	Projections of an increase in minimum temperatures likely to reduce constraint.
	The presence of acid sulfate soils and the need for drainage requires careful management of the watertable.	Projections of sea level rise are likely to increase the difficulty of managing water tables and acid sulfate soils and may potentially reduce the areas suitable for crop growth.

Quantitative Assessment of Impacts

Whilst the above provides an indicative or qualitative assessment of the likely impacts of changes in individual climate variables on sugarcane production, there is a growing demand to examine integrated impacts across the value chain. Some efforts are already underway, both nationally and internationally, to provide quantitative estimates of climate change on sugarcane production using a range of biophysical modelling capabilities. In the Australian context, a number of studies using the Agricultural Production Systems Simulator (APSIM) (Keating *et al.* 2003) together with historic climate data altered to reflect projections of future temperature, rainfall and CO_2 have been undertaken. For example, simulations of sugarcane growth were produced for the canelands at the Sunshine Coast (McDonald *et al.*, 2006) and Rocky Point (Pearson *et al.*, 2007). In the first study only the impacts of changing temperature and rainfall were considered, whereas in the second study the impact of varying CO_2 concentrations was also considered. In both cases numerous combinations of agronomic management and soil type were considered in order to examine a broad range of additional agents of change. Changes in sea level rise, rainfall intensity, number of dry days and average wind speed, while likely to impact crop productivity, have yet to be considered.

For the Sunshine Coast study sugar yields were projected to change by -2 to 7.4% by 2030 depending on soil type and crop management. Whereas at Rocky Point greater variation in potential sugar yield was simulated (i.e. 12 to -19% by 2030). A similar desk-top study was conducted on the most northerly (Mossman) and most southerly (Rocky Point) mill regions in Queensland. These also suggested yield losses by 2030, particularly in the cooler southern regions due to increased water stress (Park *et al.* 2007*c*).

In a study by Roebeling *et al.* (2007) on the land use and management options for water quality improvement in the production of sugarcane and other crop species in the Tully-Murray catchment, a similar modelling approach was used to that above to assess sugarcane production under a changed climate. Their study contained gross margin analyses on sugarcane production and showed that reduced sugarcane growth by the year 2070 could result in a change in gross margin of between -20% and 10% depending on tillage management. Simulations of bare and legume sugarcane fallow management under an altered climate at 2070 resulted in a change in gross margin of between -20% and 5%.

In order to consider the potential financial impacts of climate change on other sectors in the value chain, a preliminary analysis was conducted on the incremental impact of changes in sugarcane production on the harvesting and transport sectors of the value chain in the Maryborough region (Park *et al.*, 2007*a*). The analysis was conducted using a value chain model (Archer *et al.*, 2004; Thorburn *et al.*, 2006) and yield projections output from APSIM. The value chain model was run to produce estimates of the percentage change in costs (relative to the year 2003). The model was parameterised with the worst-case scenario estimates of yield change of -4% by 2030 (consistent with a warming of 1^oC and annual rainfall decline of 14%) and -47% by 2070 (consistent with a warming of 4^oC and decline in rainfall of 42%), respectively, for the Maryborough region. Total harvesting costs were projected to decrease by between 3 and 27%, but the cost per tonne of cane would increase by between 2 and 34% due to reduced harvesting efficiency and lower returns on capital. Total transport costs similarly reduced under reduced sugarcane yields, but increased per tonne of cane transported by up to 13%. Production in this region relies primarily on road transport as opposed to rail transport in other regions and hence can be more readily altered without incurring significant costs. This means that the impact on costs per tonne of cane in the transport sector is likely to be less than that for harvesting in this region. This is unlikely to be the case in regions where rail transport is used since it involves a large amount of capital in rail track, locomotives and wagons which are owned by the mill.

In summary, qualitative assessments suggest the greatest impacts of climate change are likely to be experienced on the grower sector of the Australian sugarcane industry (Park *et al.* 2007*c*). However, net productivity gains/losses will ultimately depend on the availability of a number of resources, particularly water, and the plant's physiological response to relative changes in all climate variables. Whilst the capacity within the sugar industry value chain is considered sufficient to absorb an increase in yield, a decrease may financially challenge many mills.

International impacts
A small number of studies detailing productivity under climate change have been produced for other sugarcane producing nations. Sugarcane yields in Trinidad are estimated to reduce by approximately 42% given a rise in mean temperature of around 2^{o}C (Singh and Mayaar, 1998), and decreases of up to 57% are predicted for sucrose yields in Mauritius at increased temperatures of 3.6^{o}C (Cheeroo-Nayamuth and Nayamuth, 2001; Nayamuth and Cheeroo-Nayamuth, 2005). In contrast, the South African sugarcane industry is projected to experience an increase in crop yield with temperature increases of up to 2^{o}C and rainfall changes of plus or minus 10% (Schulze 2007). No quantitative estimates of changes in yield have been found to date for the other major sugar-producing nations of Brazil, China, Cuba and India.

Adaptation Options

Current Options for Dealing with Climate Variability

A number of web-based sources of information and tools are presently available (or in design) to assist sugarcane industry stakeholders manage climate variability through informed decision making. These include the tools and information sources detailed in Chapter 1 which are generally applicable to a wide range of agricultural industries. Table 5.3 details decision support tools and forecasting systems more specifically designed and tested for the Australian sugarcane industry.

The tools and forecasting systems detailed in Table 5.3 are used to support a range of management decisions that are impacted by climate, and for which reliable seasonal climate forecasts are available. Technologies presently exist to help optimise planting and harvesting dates, the scheduling of limited irrigation water, nitrogen fertiliser management (for both optimal production and minimal environmental impact), drying-off strategies, and the design of on-farm water storage facilities. One example is the ENSO El Nino/Southern Oscillation signal. This can be used early in the year in certain sugarcane-growing regions to predict likely climate, and hence sugarcane productivity, around the time of harvest. Having this information 7 months prior to harvest enables the scheduling of harvest start date to be optimised for productivity. Such information is also useful to marketers planning customer allocations, shipping schedules and storage requirements for the next season, and has been found to provide financial benefits for the industry (Anthony *et al*. 2002).

Table 5.3: Decision support tools and sources of information for managing climate variability that have been specifically developed or applied to the Australian sugarcane industry. Sectors utilising the tools or information sources are indicated as follows: (1) value chain, (2) grower, (3) harvest and transport, (4) milling, and (5) marketing.

Tool/information source/use	Web address/reference	Details
Rain Gauge CD (2,3,4)	Everingham (2002)	Utilises patched point data to produce regional-wide climate forecasts for sugarcane farmers in the Herbert region. This tool was used to demonstrate that whilst rainfall amounts vary across the region, the chance of exceeding specified rainfall amounts remains constant.
Recipes and Rain Gauges (2,3,4)	Everingham (2002)	Provides a step-by-step guide to climate forecasting in the Herbert region. The book contains short stories about how growers and millers in the Herbert have used seasonal climate forecasts.
Excel-based rainfall forecasting (2,3,4)	Contact Andrew Wood, CSR, Ingham	Following on from project CTA036, CSR in the Herbert produced their own forecasting system using Excel. Research staff have used this tool to provide climate forecasts for inclusion in the local newsletters and internet site.
RainForecaster (2,3,4)	Everingham *et al.* (2006); Everingham (2007*a*)	Computer-based tool that produces 3-monthly forecasts of rainfall and wetdays. The program is run by local coordinators to produce climate updates and forecasts tailored to their region. Initially designed to provide forecasts for the case study regions (SRDC project CSE009), but is also utilised by Tully, NSW, Camilla, Koumala and Plane Creek regions.
Marketing, Climate Forecasting Compendium (4)	Everingham (2002)	Booklet for marketers that summarises how seasonal climate forecasts can impact on rainfall and sugarcane yields.
WaterSense (2)	Inman-Bamber *et al.* (2005, 2006) www.clw.csiro.au/watersense/pages/main.aspx	Web-based irrigation water optimising tool for determining the best time to irrigate sugarcane with a limited amount of irrigation water at a paddock level. The tool utilises an APSIM-Sugarcane like model to devise an optimum irrigation strategy that simultaneously minimises overall crop water stress and provides the highest possible crop yield. WaterSense is presently linked to 21 SILO and automatic weather stations and could be expanded. WaterSense can now also be used in a full irrigation mode where water stress can be practically eliminated.
Irrigation scheduling (2)	Inman-Bamber *et al*. (2001)	Uses APSIM simulations together with long-term climate records to determine the optimum timing of limited irrigation in Bundaberg and the impacts of El Nino and La Nina conditions on irrigation management.

Tool/information source/use	Web address/reference	Details
Nitrogen management (2)	Everingham *et al.* (2006)	Used to determine optimum nitrogen fertiliser application timing and the amount of maximum productivity and minimum environmental losses given the SOI phase. Uses APSIM simulations and historic climate data. The technology was developed for a project group in the Tully region, but as the results were confounded, it is presently not in use. Further research is continuing.
Long lead forecasting system using the ENSO signal (2,3,4)	Everingham *et al.* (2007*a*)	Use of a statistical model to predict the likelihood of harvest rainfall (August to December) in the NSW sugarcane regions using the previous La Nina signals in January, February and March (thereby eliminating the autumn predictability barrier). Offers the NSW sugar industry a valuable source of information to aid decisions that must be made early in the year that impact rainfall-dependent operations much later in the year.
Long lead forecasting system for estimating yield size (5)	Everingham *et al*. (2007*b*)	Uses a Bayesian discriminant analysis procedure to determine the likelihood of a small, medium, or large crop across 4 major sugarcane-growing regions in Australia (Ingham, Ayr, Mackay, and Bundaberg) for use as marketing intelligence. Compared with the current industry approach, the discriminant procedure provided a substantial improvement for Ayr and a moderate improvement over current forecasting methods used in the other 3 regions, with the added advantage of providing probabilistic forecasts of crop categories.
Long-lead rainfall forecasts (1)	Everingham *et al*. (in press *a*)	A long-lead statistical ENSO prediction model aimed at reducing the risk associated with decisions that must be made before autumn and are effected by rainfall anomalies post-autumn. The outcome can provided an early indication of the likelihood of disruption to harvest due to wet conditions in a year.
ENSO El Nino/Southern Oscillation signal (5)	Everingham *et al.* (2003; 2001*a*)	The five phases of the southern oscillation index are used for certain sugarcane growing regions to indicate sugarcane yield anomalies 7 months prior to the commencement of harvest. Advance knowledge of crop size can assist industry decision makers in scheduling when the harvest season should commence and be used by marketers to improve planning of customer allocations, shipping schedules and storage requirements for the next season.
Decadal forecasting system (2,3,4)	Jaffres and Everingham (2005)	Based on a relationship between long-term variations in sea surface temperature (SST) and mean sea level pressure (MSSLP) for a number of sugar-growing locations on the east coast of Australia. Whilst a strong relationship between decadal rainfall and the indices was uncovered, it is recommended that further research be conducted to clarify whether this relationship is a statistical artefact or it is underpinned by a physical phenomena.
Irrigation optimisation (1)	Park (2006); Everingham *et al*. (2006)	Study conducted into the usefulness of the three- and five-phase seasonal climate forecasting systems in determining the optimal timing of irrigation events (and hence maximum crop yield). The forecasting systems were used in conjunction with an APSIM routine (Inman-Bamber *et al.* 2001) to assess maximum crop yield

Tool/information source/use	Web address/reference	Details
		attainable under historic climate scenarios. The model simulations revealed that growers who followed an irrigation schedule tended to have higher yields in La Nina type years and that for selected soils and locations there was a slight tendency for the model to schedule irrigations earlier in El Nino years.
Relationship between ENSO and decadal systems (2,3)	Jones and Everingham (2005)	Demonstrates an absence of intensified harvest rainfall amounts for 7 sugarcane growing regions suggesting a close watch be kept on ENSO signals such as the southern oscillation index and equatorial sea surface temperatures to gain insight about conditions for the coming season.
Comparison of phase based seasonal climate forecasting systems (2,3)	Everingham (2007*b*); Jones and Everingham (2006); Everingham *et al*. (2006)	Statistically compares a number of climate forecasting systems against the five-phase SOI system (Stone *et al.* 1996), i.e. the benchmark forecasting systems used in the Australian sugar industry. These systems included two versions of the three-phase, or ENSO forecasting system, the nine-phase SST system (Drosdowsky and Chambers 1998; Drosdowsky 2002) using several performance measure criteria.
Estimation of risk associated with drying-off strategies (2)	Robertson *et al.* (1999)	Study linking the relationships between cane yield, cane dry weight and sucrose concentration to APSIM and long-term climate data to determine the economically optimum duration of drying off in the sugarcane crop, and its variability from season to season for 2 locations in Australia and one location in South Africa, and for a range of harvest dates and soil types.
Value chain based decision-making (1)	Everingham *et al.* (2002*a*)	A comprehensive systems approach for using seasonal climate forecast systems to improve risk management and decision-making capability across all sectors of the sugarcane industry. The application of this approach is outlined for decisions relating to yield forecasting, harvest management, and the use of irrigation.
DamEa$y (2.)	Lisson *et al.* (2003)	A decision support tool developed principally for extension officers or industry consultants working in collaboration with, or on behalf of, farmer clients wanting to investigate the economic, cane yield and environmental implications of incorporating an on farm water storage into an existing sugarcane farming enterprise.
Value chain based decision-making (1)	Everingham *et al*. (2002*b*)	Investigates the utility of climate forecasting systems to assist industry planning at the farming, harvesting, milling and marketing components. The research demonstrated the potential to improve industry management by (i) forecasting Burnett River streamflows to improve knowledge of water availability for irrigation; (ii) forecasting harvest season rainfall to improve scheduling, and (iii) forecasting sugarcane yields to assist forward selling by marketers. Demonstrates that due to the autumn predictability barrier, seasonal climate forecasts are not able to assist millers with planning for the season ahead.
Forecasting	Everingham *et al*. (2001*b*)	Analysis of a climate forecasting system to forecast unseasonally high rainfall in the May-June and October-

Tool/information source/use	Web address/reference	Details
wetdays during the harvest season (2,3,4)		November that typically affects crush start time, timing of sugar supply, harvest season length and ratooning capability for the following season. The climate forecast system offers some benefits associated with forecasting 'wetdays' during October-November, but is more limited for forecasting 'wetdays' during May-June.
Forecasting water allocations (2)	Everingham *et al*. (in press *b*)	Outlines a process for forecasting water allocations using phases of the southern oscillation index for canefarmers on the southern Bundaberg Water Supply Scheme. Also links forecasted allocations to an irrigation scheduling system.
Forecasting sugarcane yields (3,4)	Kuhnel (1994)	Demonstrates the relationship between the Southern Oscillation Index and the sugarcane yield anomalies at 27 mills in Queensland. It showed the SOI to be a useful indicator of yields for the northern sugarcane districts, less so as predictor of total sugarcane yields over large areas.

Adaptation Options for Dealing with Climate Change

The sugarcane industry in Australia has a long record of managing the impacts of weather and climate-related events. Nevertheless, additional adaptation measures will be required to reduce the adverse impacts of projected climate change and variability, regardless of the scale of mitigation undertaken over the next two to three decades. (IPCC 2007). Similar to other cropping systems, many of the management-level adaptation options suitable to the sugarcane production system (detailed in Table 5.1 and Table 5.2 above) are largely extensions or intensifications of existing climate risk management or production enhancement activities in response to a potential change in the climate risk (Howden et al., 2007). Adaptation strategies can be categorised into the following approaches:

Improved management of limited water supplies – this may be achieved through more efficient use of water supplies (e.g. the use of more efficient irrigation water delivery technologies and schedules, improved soil structure for improved infiltration and moisture conservation, and trash blanketing, and minimum tillage for reduced evaporation); improved capture and storage of water (e.g. harvesting rainfall and excess surface water in on-farm storage facilities, laser levelling and the re-use of tail water), and the maintenance of below-ground water sources (e.g. restrictions on groundwater pumping and the construction of new bores, abandonment of saline bores, ongoing monitoring of water quality). Integration of streamflow forecasting, storage options and crop water demand could also go a long way to improving the use of catchment runoff for crop production. A change in pricing and regulations, such as the date of the water year, would also help create incentives for more efficient use of catchment runoff.

Technological fixes – these might be achieved through technologies currently on the market or those which await invention, refinement or delivery. Technological fixes may include improved varieties with desirable traits consistent with prevailing climate conditions (e.g. greater drought resistance, water use efficiency, tolerance of increased temperatures, reduced lodging, low vegetative growth and stalk fibre content); or machinery technologies (e.g. wet-weather harvesters and machinery able to effectively harvest lodged cane, and improved within-mill clarifier design and modified mud scrapers). These technical fix adaptive options are generally based on reductionist analysis, engineering design principles, and computer-aided modeling, as opposed to more attitudinal fixes that require a change of thought process or behaviour.

Cropping system design and agronomic management strategies – these may include farm-scale planning and design (e.g. tree planting for shelter and soil protection, introduction of precision agriculture, laser levelling, diversification into alternative/additional crop species), or improved and more flexible agronomic management (e.g. adjustment of planting dates and crop varieties; revision of best management practice for erosion, pest, disease and weed control, trash blanketing, nutrient cycling and improved soil structure, and the optimisation of resources to achieve maximum yield in the prevailing climate). These adaptive options require a greater element of attitudinal change than the technical fixes detailed above.

Improved decision-making – this may be achieved through the utilisation of decision-support tools and information (Table 5.3), especially those incorporating seasonal climate forecasts, to reduce production risk.

Institutional change – these might include physical infrastructure (e.g. construction of seawalls and storm surge barriers, dune reinforcement, land acquisition and the creation of marshland/wetlands as buffer zones against sea level rise and flooding, and the protection of existing natural barriers), industry reform (e.g. revision of quarantine boundaries, relocation of the sugarcane production to ore southerly areas to track poleward shifts of climate zones, increased flexibility in capacity and operations in the value chain to track changes in the quality and quantity of throughput to maintain optimal efficiency), or greater diversification into alternative rural enterprises and off-farm income.

The adaptation strategies in Table 5.1 and Table 5.2 and noted above, are qualitative in nature and fail to estimate the extent or scale of the adaptation action required. Eco-physiological models, such as APSIM, provide a useful means to not only quantify the potential impacts of climate change in terms of crop yield, but also the assess the efficacy of adaptation strategies to ameliorate the negative effects and capitalise on the possible benefits of a change in climate.. For example, Park *et al.* (2007*c*) used APSIM to simulate sugarcane planting at Rocky Point 60 days earlier than is currently practised. This increased simulated median cane yield by up to 5% on 1990 levels for 2030 , whilst delaying planting by up to 30 days had little effect on crop productivity. In contrast, simulated planting 60 days earlier in the Mossman region showed a decrease in yield by nearly 10%, whilst planting up to 30 days later in the season, increased yields by up to 3%. The quantitative study highlights the importance of accounting for regional biophysical and institutional differences across the Australian sugarcane industry when considering both the impact of climate change and adaptation strategies. Interestingly, the simulation study also suggested that a change in planting date of up to 60 days earlier and 30 days later than is presently practised is unlikely to fully ameliorate yield losses resulting from changes in rainfall and temperature by 2030 in the Rocky Point region. A later planting date in Mossman may offset much of the potential yield losses predicted for the region. This method can be extended to a range of adaptation strategies including changing the time and duration of the harvest season, variety selection and irrigation practices.

Risks of Maladaptation

No research has to date been undertaken explicitly defining the risks of maladaptation to climate change for the sugar industry. However, the approach taken in Park *et al.* (2007*b*) which expresses impacts and adaptation strategies in a value chain context, highlights a number of possible conflicts. Some maladaptation risks include:

- An extended harvest season may be a positive impact for the harvesting, transport and milling sectors since it would reduce the requirement for capital stock (harvesters, trucks, etc), but it may be negative for the growing sector since a greater proportion of the crop may be required to be harvested at a time of year when CCS levels are less than optimal.
- An increased use of irrigation water in some areas may result in an increased risk of salinity or exacerbation of a rising water table
- The use of increasing volumes of trash on the soil surface may immobilise soil N stores to below crop demand, necessitating an increased amount of N fertiliser to be used (and increased greenhouse gas emissions and increased risk of off-site impact).
- The removal of trash from the paddock for co-generation (as a mitigation strategy) has the potential to reduce crop yields (primarily through a reduction in the input of C and N to the soil) and increase the cost of alternative weed control measures (Thorburn *et al.*2006). It is also likely to negatively impact erosion control and soil moisture retention.

Adaptation strategies must also be regionally-specific in design, as exemplified by a change of planting date having a differential response on yield in simulation studies conducted for the Mossman and Rocky Point cane regions (Park *et al.* 2007*c*). It will also be necessary to iteratively develop and apply adaptation strategies in line with progressive changes in climate to avoid maladaptation.

Costs and Benefits

Whilst only a few studies (Roebeling *et al.* 2007; Park *et al.* 2007*a*) have made preliminary studies of the cost of climate change impact on the Australian sugar industry (see the section above on climate change impacts), these studies have been conducted for a single region and been limited to considering changes in only temperature and the amount of rainfall. Clearly there is a need for further analysis of the costs and benefits of climate change on sugarcane production in Australia.

Knowledge Gaps and Priorities

In the recently published SRDC Climate Change Technical Report (Park *et al.* 2007*a*) it was concluded that further R&D projects should address the following knowledge gaps and priority research, development and extension (R,D&E) areas:

- Improvements in farming practice, especially precision irrigation, on-paddock water use and off-paddock water quality impacts and the management of increased climate variability through seasonal forecasting;
- Innovative farming and processing systems that take an integrated and sustainable approach to risk and opportunity across all inputs such as plant varieties, nutrient management practices and energy use in mills, through to the outputs of sugar, fertiliser and bio-energy, ensuring a flexible and financially resilient industry;
- Capitalisation of bio-energy opportunities and carbon trading potential for value adding and preferably integrated within innovative farming and processing systems to maximise cross industry benefits;
- Greater focus in sugarcane physiology and plant improvement in varietal characteristics that enhance resilience to climate change, industry adaptation to higher temperatures, reduced water availability, and extreme events. This will also require knowledge of the genetic x environment x management (G*E*M) interactions.
- Enhancing human capital through building skills and enhancing science capability in climate understanding and risk management across the sugar industry so that the knowledge and tools required by the industry may be delivered;
- Linking of biosecurity management to a changing climate so that potential threats in biosecurity are understood;
- An understanding of the global context of climate change impacts on worldwide production, profitability and markets relative to the Australian sugar industry to help continually optimise market position.

Park *et al.* (2007*a*) note that many of the knowledge gaps detailed above can be best filled through the enhancement of existing R,D&E activities. For example, research into plant agronomy, physiology and plant genetics already incorporates many of the key attributes of climate, albeit with increased emphasis on climate related attributes called for as part of the response to a changing climate. Likewise, research on sustainability of on-farm practices is already addressing issues regarding off-farm pollutant and enrichment. A more variable and event-driven climate will make this research even more imperative if the sugarcane industry is to respond to community demands and demonstrate resilience.

Many of the knowledge gaps detailed above can be best filled through the enhancement of existing R, D&E activities. Other knowledge gaps are more specific to climate change science and increasing climate variability. One of these applications may be in predicting climatically-optimal growth locations for the relocation of sugarcane production. In addition, building social capital through targeted extension, improving skills and providing a more industry-wide knowledge base are all essential. Additional knowledge gaps will undoubtedly come to light as the sugarcane industry responds to a changing climate.

Table 5.4: Summary of climate change adaptation options for the sugarcane industry indicating whether the option 1) has already been assessed or is a remaining knowledge gap, 2) is highly feasible, 3) would be feasible / effective immediately, or 4) should be a high priority for research, assessment and implementation in developing adaptation strategies.

Adaptation options	**Options already assessed**	**Options with high feasibility**	**Immediacy**	**Priority activities**
Policy level				
Develop linkages to existing government policies and initiatives e.g. GGAP, Greenhouse challenge, salinity, water quality, rural restructuring	X	✓	✓	✓
Ensure communication of broader climate change information	✓	✓	✓	✓
Maintenance of effective climate data distribution and analysis systems	✓	✓	✓	✓
Modification of existing Federal and State Drought policies to encourage adaptation	X	X	✓	X
Continue training to improve self-reliance and to provide knowledge base for adapting	✓	✓	✓	✓
Policy settings that encourage development of effective water-trading systems that allow for climate variability and support development of related information networks	✓	✓	✓	✓
Public sector support for a vigorous agricultural research and breeding effort with access to global gene pools	✓	✓	✓	✓
Maintain R&D capacity, undertake further adaptation studies which include costs/benefits and streamline rapid R&D responses	✓	✓	✓	✓
Develop further crop systems modelling capabilities such as APSIM and quantitative approaches to risk management	✓	✓	✓	✓
Encourage appropriate industry structures to enable flexibility	X	X	✓	X
Encourage diversification of farm enterprises	✓	X	✓	X
Ensure support during transition periods caused by climate change and assist new industry establishment	X	✓	X	X
Altering transport and market infrastructure to support altered production regimes caused by climate change	X	✓	X	X
Encourage financial institutions to be responsive to changing industry needs	X	✓	X	X
Continuing commitment from all levels of government for pest, disease and weed control including border protection	✓	✓	✓	✓

Adaptation options	Options already assessed	Options with high feasibility	Immediacy	Priority activities
Introduction of climate change adaptation into Environmental Management Systems	X	✓	✓	✓
Crop and farm management				
Development of participatory research approaches to assist pro-active decision making on-farm	✓	✓	✓	✓
Develop further risk amelioration approaches (e.g. zero tillage and other minimum disturbance techniques, retaining residue, extending fallows, row spacing, planting density, staggering planting times, erosion control infrastructure)	✓	✓	✓	✓
Develop further controlled traffic approaches – even all-weather traffic	✓	✓	✓	X
Research and revise soil fertility management (fertilizer application, type and timing, increase legume phase in rotations) on an ongoing basis	✓	✓	✓	✓
Alter planting rules to be more opportunistic depending on environmental condition (e.g. soil moisture), climate (e.g. frost risk) and markets	✓	✓	✓	✓
Expand routine record keeping of weather, production, degradation, pest and diseases, weed invasion	X	✓	✓	✓
Tools and extension to enable farmers to access climate data and interpret the data in relation to their crop records and analyse alternative management options.	X	✓	✓	✓
Climate information and use				
Improve dynamic climate modelling tailored towards decision making in agriculture	✓	✓	✓	✓
Incorporate seasonal forecasts and climate change into farm enterprise plans so as to be able to readily adapt	✓	✓	✓	✓
Maximise utility of forecasts by R, D&E on combining them with on-ground measurements (i.e. soil moisture, nitrogen), market information and systems modelling.	✓	✓	✓	✓
Warnings prior to planting of likelihood of very hot days and high erosion potential	✓	✓	X	✓
Water resource issues				
Further improvements in water distribution systems (to reduce leakage and evaporation), irrigation practices such as water application methods, irrigation scheduling and moisture monitoring to increase efficiency of use	✓	✓	✓	✓

Adaptation options	Options already assessed	Options with high feasibility	Immediacy	Priority activities
Maintain access rights to water	✓	?	✓	?
Develop water trading system (and associated information base) that can help buffer increased variability	X	?	✓	?
Maximise water capture and storage on-farm – needs R&D and policy support	✓	✓	✓	✓
Managing pests, disease and weeds				
Improve pest predictive tools and indicators	✓	✓	X	✓
Improve quantitative modeling of individual pests to identify most appropriate time to introduce controls	✓	✓	X	✓
Further development of Area-wide Management operations	✓	✓	X	✓
Further development of Integrated Pest Management	✓	✓	✓	✓
Improved monitoring and responses to emerging pest, disease and weed issues	✓	✓	✓	✓
Crop breeding				
Selection of varieties with appropriate thermal time and vernalisation requirements, heat shock resistance, drought tolerance (i.e. Staygreen), high protein levels, resistance to new pest and diseases and perhaps that set flowers in hot/windy conditions	✓	?	✓	✓
Ongoing evaluation of cultivar/management/climate relationships	✓	✓	✓	✓
Land use				
Potential for cotton, summer-growing grains and pulses further south	N/A	N/A	N/A	N/A
Movement to more livestock in the enterprise mix	X	✓	X	X

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6: VITICULTURE

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Key Messages:

- A warmer climate will hasten the progression of phenological stages of the vine so that ripening will occur earlier in the season.
- Budburst may be affected in some of the more maritime climates due to less chilling over the winter dormancy period.
- Grape quality will be negatively impacted if no adaptation measures are implemented.
- Water demand for winegrape vines will increase in a warmer climate while rainfall and, more importantly, runoff to water storages is projected to decrease.
- Shifting to cooler sites can alleviate some of the warming impact. As vineyards have a life of 30+ years, planning for this should begin now.
- Within regions, existing varieties can be replaced with ‘longer season’ varieties to compensate for the warmer temperatures and compressed phenology.
- Winery infrastructure and staffing levels need to accommodate more compressed vintages, i.e. possible increased intake over a shorter period.
- Consumer education to accept new wine styles and varieties will be important.

Figure 6.1: Sauvignon Blanc vineyards (Photo: Ashley Wheaton).

Introduction

The Australian wine industry is an important contributor to the Australian economy with wine exports being the third largest valued agricultural export commodity behind wheat and beef products (ABARE 2006). Exports for the year 2007 are reported to be AU$3billion. The industry currently occupies 160,000ha (Fletcher *et al.* 2007) with winegrape production expanding markedly in the 10 years until 2004 (Gordon 2004) but reduced since then due to climatic and economic influences (Fletcher *et al.* 2007). With expectations of reduced amounts of water available for irrigation in the warm inland districts, yields may be below average again in 2008 (AWBC 2007).

Winegrapes are planted in diverse climatic regions in Australia (Smart *et al.* 1980) mainly between the latitudes of 30ºS-40ºS (Figure 6.2). There are currently 60 wine growing regions and these have been legally defined and described (AWBC 2006). These regions range in climate type from some of the warmest wine growing regions of the world to cool climate regions capable of producing more delicate wine styles (Johnson 1989). For the purposes of assessment where 10 climatic zones are being assessed (see Table 1-3 in the introductory chapter of this document), the 'Mediterranean' and 'cool-climate temperate' climate zones contain the majority of the wine regions of Australia (Hobbs and McIntyre. 2005).

The wine industry is particularly interested in climate change because the production of fine wine is intimately wedded to the concept of *terroir:* matching premium grape varieties to particular combinations of climate and soils to produce unique wines of particular styles (Seguin 1986). Changes in climate will alter these *terroirs* and challenge the adaptive capacity of the industry. Investors in the wine industry as well as consumers of its output are therefore alert to the prospect of such consequences stemming from climate variability and change and are increasingly exploring the available options to enable the industry to adapt to change.

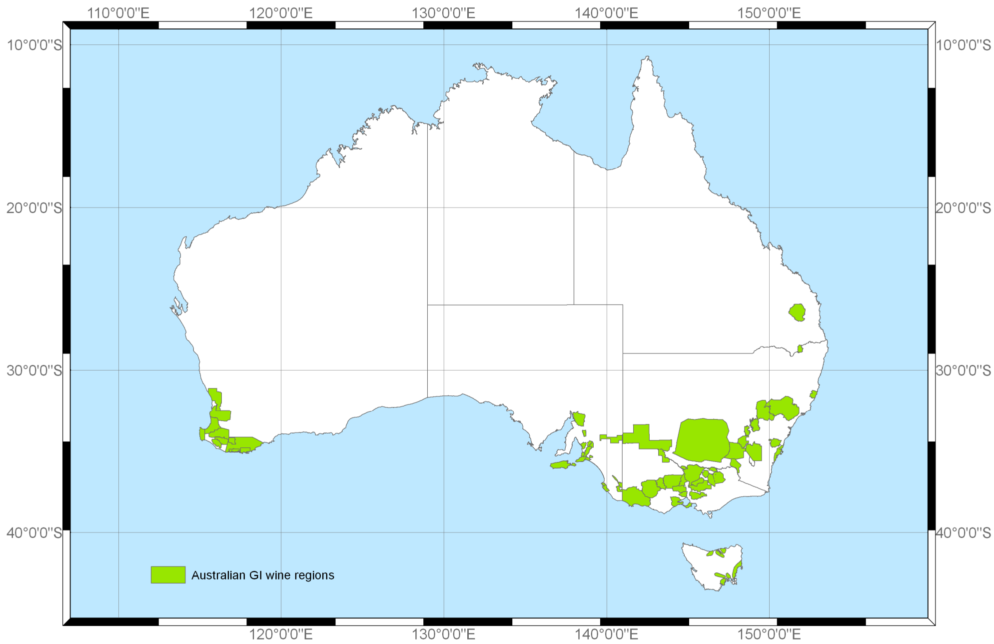

Figure 6.2: Australian Geographic Indication (GI) wine regions (green areas).

Climate Change Impacts

Impact of temperature increase

Phenology

Winegrape vines *(Vitis Vinifera)* have four main developmental stages: budburst, flowering, veraison (colour change and berry softening), and harvest (grape maturity) (McIntyre *et al.* 1982). The duration of these phenological stages varies greatly with grapevine variety, climate, and geographic location (Jones and Davis 2000). Matching the developmental phases of grapevines to a climate is an important factor in the planning of any vineyard development where optimizing quality is a priority. A warmer climate will hasten the progression of phenological stages of the vine so that ripening will occur earlier (Jones and Davis 2000; Jones *et al.* 2005a; Webb *et al.* 2007b). This will impact on the Australian wine industry in positive and negative ways depending on the present climate of the region. Maintaining consistency of quality is the biggest challenge to the Australian wine industry under global climate change scenarios.

Greenhouse gas-induced climate change will affect warmer viticulture regions (e.g. Swan Valley (WA), Sunraysia, Riverina, Hunter Valley). Grapes are monitored for sugar, acidity and flavour levels as these develop through the ripening period. The aim of the winemaker is to harvest the crop when the balance of these compounds will be expected to produce the desired wine style. The rate of change in these compounds is temperature dependent with higher temperatures increasing the speed of development. Consequently, higher ripening temperatures allow for a narrower window from which to determine the optimum harvest time. In cooler climates in more southerly parts of Australia (Tasmania, Mornington Peninsula) global warming may allow varieties that are marginal now to be grown and ripened more fully. In intermediate climates the season will begin earlier and phenological stages will be accelerated leading to ripening in the earlier hotter months with the chance of reduced quality.

Warmer winter temperatures may cause problems due to lack of winter chilling as suggested by Dry (1988). Many perennial plants have a physiological requirement for a quota of cold temperatures through the dormancy period, known as a chilling requirement, before budburst will commence (Lavee and May 1997). The mean July temperature in the Margaret River, WA, (13.2°C) is already known to be associated with problems of lack of dormancy (Dry 1988) and a recent study has highlighted the reducing trend in the hours of chilling in this region (Lyons and Considine 2007). Winter temperatures may increase by about 0.3°C - 1.5°C by 2030 in most winegrape growing areas (Whetton, 2001). This may cause a reduction in chilling and resultant problems with non-uniform dormancy breaking.

The phenological shifts will also result in shorter harvest periods with varieties presently being harvested sequentially, perhaps reaching maturity more synchronously (Webb *et al.* 2007b). Attendant problems for intake scheduling may also make it increasingly difficult to process each and every batch of fruit when quality is deemed 'optimal'. This may have implications to infrastructure and staffing over the vintage period.

Winegrape and wine quality

The quality of winegrapes is affected by temperature in that higher ripening temperatures can lead to a reduction in colour for red winegrapes (Haselgrove *et al.* 2000; Mori *et al.* 2007) and altered aroma profiles of white and red winegrapes (Marais 2001; Marais *et al.* 2001). Modelling studies assessing the projected impact of climate change on winegrape quality (Webb *et al.* 2007a) and wine quality (Jones *et al.* 2005b) indicate that, provided grapes are able to ripen in a given climate currently, if the climate warms, quality will be negatively impacted (assuming no adaptive measures are taken).

In a warmer than ideal environment, the grapevine will go through its phenological events more rapidly resulting in earlier and likely higher sugar ripeness. While the winemaker is waiting for the flavours to develop, acidity is lost, leading to a risk of less well balanced wine (Jones 2007). A trend of increasing alcohol levels has been noted in some studies (Duchene and Schneider 2005; Godden and Gishen 2005).

Changes in frequency of extreme events are likely to occur more rapidly than changes in climatic averages. An increase in the frequency of days over 35°C from an average of 32 days during the 1971-2000 period to 39 days by 2030 or 45-60 days by 2070 for Mildura, for example, is projected (CSIRO and BoM 2007). This increase in extreme temperatures will have the greatest effect on viticulture in currently warm to hot areas. Studies focussed on the effect of extreme temperatures on grapevines and determinations of any threshold for 'damage' remain to be made. Anecdotal evidence describing vine 'shut-down' and sunburn impact are well described.

Australian viticulture is concentrated in cool southern regions and is affected by indigenous insect pests, especially light brown apple moth (LBAM), and fungal diseases like downy mildew, powdery mildew, black spot, botrytis (which is helped by LBAM infestation) and *Phomopsis*. All of these are strongly influenced by climate (Bob Sutherst, pers. comm). Increasing temperatures, especially night-time temperatures, may increase the number of Downy Mildew primary infections. Temperatures falling below 10 degrees at night currently eliminate the possibility of many primary infections. The current trend towards increased night-time temperatures, if continued into the future, may result in significantly increased risk of Downy Mildew and related diseases (Magarey *et al.* 1994b).

Impact of increase in carbon dioxide concentration

Increased growth of vines under higher atmospheric carbon dioxide (CO_2) concentrations may lead to problems of excessive vegetative development and within-canopy shading (Dry 1988), whereby the grapes can be excessively shaded by the surrounding canopy. Studies showing the effect that within-canopy shading decreases potential fruitfulness have been numerous (May *et al.* 1976; Smart and Robinson 1991). This will tend to occur only if water is limiting growth to some extent, as CO_2 effects are usually small when water availability is high (May *et al.* 1976; Smart and Robinson 1991).

Increased concentrations of CO_2 in the atmosphere result in reduced stomatal conductance (Long *et al.* 2004). Whether this affects water use efficiency of the whole crop depends on whether increased leaf surface area, caused by the increased growth in enriched CO_2 environments, counteracts the effect of reduced stomatal conductance. (Gifford 1988) found that the rate of soil water depletion was not appreciably altered in enriched CO_2 environments with an almost exact trade-off between reduced transpiration per unit leaf area and increased leaf area.

The effect of increased CO_2 and temperature on the growth of vines *in situ* has been modelled for Europe (Bindi *et al.* 1996). The model predicted a 35% increase in fruit yield if CO_2 was increased from 350ppm to 700ppm **without** a corresponding temperature increase. An increased temperature caused a decreased length of growing season (discussed previously) and resultant decreased yield. Bindi, Fibbi *et al*. (1995) have shown that the effect of **both** CO_2 and temperature increases together will mean that average crop yield will change as a result of climate change. Overall, simulations did not provide a conclusive answer to the question of whether the potential negative effects of the warmer temperatures would be compensated for by CO_2-fertilization effects under climate change.

In addition to changes in mean crop yield, models also detect increases in year-to-year variability of crop yields. The difference between very high yields achievable in good years under increased atmospheric CO_2 concentrations and lower yields in bad years will be larger than at present, implying a higher economic risk for growers (Bindi *et al.* 1996).

Plants grown in elevated atmospheric CO_2 typically have lower protein and nitrogen concentrations (Drake *et al.* 1997; Morison and Lawlor 1999) and this may influence fermentation processes. The survey by Drake *et al.* (1997) found that the carbon:nitrogen ratio (C:N ratio) will increase in plants. In winegrape juice such an effect would reduce the availability of nitrogen for yeast nutrition during fermentation, increasing the risk of a fermentation failure.

The importance of nitrogen on yeast nutrition is well understood. Many wineries measure FAN (free amino nitrogen); and YAN (yeast available nitrogen) and adjust winegrape juice accordingly. However, research into the effect of increasing atmospheric CO_2 concentrations on the quality of wines has not been undertaken broadly, although some research is occurring in Europe. If amino acid levels of winegrape-juice are affected the consequences of this on quality will need to be studied.

Impact of water balance changes

Reduced water supply

Annual rainfall totals for most of the grape growing regions may decrease by 2% to 10% by 2030 and 5 to 20% by 2070 (CSIRO and BoM 2007). Because of the variation in annual rainfall between the different winegrowing regions, the impact this may have on viticulture will need to be assessed region by region. Seasonally, for most regions, the greatest percentage reduction in rainfall is in spring, with little change in summer. The Hunter Valley is one of the few winegrowing regions likely to experience an increase in summer rainfall.

CSIRO has calculated projections of change in potential evaporation (atmospheric water demand) and regardless of whether the rainfall is projected to increase or decrease, increases in potential evaporation occur in all seasons in the winegrape growing regions of Australia (CSIRO and BoM 2007). The increases tend to be larger where there is a corresponding decrease in rainfall (Kirono *et al.* 2006).

The reduced rainfall and higher evaporation results in reduced runoff to farm dams, streams and rivers (Cai and Cowan submitted; Jones and Durack 2005). This factor will have more impact on the viticulture industry than rainfall decline alone. The majority of vineyards in Australia rely on a secure irrigation supply (McCarthy *et al.* 1992). When water is not available, yields can decline (AWBC 2007).

Vineyards sourcing their own local surface and underground water with no access to public irrigation schemes were thought to be more vulnerable than those with access. Allocations from public irrigation schemes have been reduced to 16% of the normal allocation in South Australia in the current drought (2007/08 season) and the reliability of what was thought of as a relatively secure supply is now being questioned (MDBC 2007). The general pressure on water supplies will mitigate strongly against the licensing of more farm dams or bores with regulations/restrictions already existing on amounts being drawn from underground water sources in some areas.

Growing season rainfall is conducive to fungal disease (Magarey *et al.* 1994a). Rain, especially after veraison, plus associated humidity, predisposes grapes to berry splitting, Botrytis, and other fungal diseases. According to climate projections growing season rainfall is likely to reduce in most winegrape growing regions. As a result climate change is likely to be associated with a decreasing risk of fungal disease.

If summer rainfall increases, as may occur in the Hunter Valley, and with lower probability in other regions, fungal pressure may increase. Increased evaporation in the grapevine canopy created by higher temperatures will decrease leaf wetness, and hence fungal pressure, so there may be no overall change in susceptibility to fungi. If the effect of increased evaporation does not offset possible increases to rainfall increased fungal problems may occur.

Even where mean rainfall may decrease, extreme rainfall may increase. Extreme rainfall events may increase by up to 4% in south-eastern Australia in autumn (CSIRO and BoM 2007), which is the period in which harvest occurs for winegrapes. *Botrytis cinerea*, or grey mold, can devastate winegrape crops. This fungus develops in wet and humid conditions. Heavy rainfall in the harvest period predisposes the crop to this fungus.

Figure 6.3: *Botrytis* affecting some Riesling berries.

Frost

Climate change projections indicate fewer frost days so it might be expected that a warmer climate would experience less frost damage. However, as budburst itself will be earlier, frost risk may not be greatly reduced (Nemani *et al.* 2001; Smart 1989)).

Reduced rainfall is projected for spring when shoots are emerging and the potential for impact of frost damage to reproductive parts of the vine is at a maximum. Drier soil, fewer clouds and lower dew points may increase both frost occurrence and frost severity. One recent example of increasing frost in a warming climate occurred in 2006, the warmest spring on record (since 1950) in southern Australia (BoM 2007). Indeed, widespread frost damage occurred in seasons coinciding with both of the most recent Australian droughts (i.e. 2002/03 and 2006/07). In the 2006/7 season the severe frosts, along with the drought, were deemed responsible for the severely reduced national winegrape yield (AWBC 2007).

Salinity

Salinization of arable land is already a significant problem in Australian agriculture. This is particularly the case in the more intensely irrigated areas in Australia's southeast and in dryland agriculture regions throughout southern and north-eastern Australia. There is very limited research in the area of climate change and soil salinity effects in relation to grapevines. Investigations into other agricultural systems suggest that the amount of groundwater recharge may reduce significantly across southern Australia (Howden *et al.* 1999; van Ittersum *et al.* 2003) but that the relative impact on recharge and on aquifer productivity varies by region, by soil type and by management techniques. In the main grape growing areas, whilst the longer-term risk of salinisation may be decreased by climate change (due to lower rainfall/recharge), there may be a short-term risk with reduced streamflows.

Fire

A link has been identified showing smoke significantly influences the chemical composition and sensory characteristics of wine and causes an apparent 'smoke taint' (Kennison *et al.* 2007). Australian grape growers claim wildfires cost them more than $7.5 million in lost revenue during the 2003 and 2004 vintages due to smoke taint. The Canberra bushfires of 2003 resulted in heavy smoke damage, while growers in Victoria suffered at least $4 million losses from fires in adjoining national parks. With incidence of bushfires projected to increase in the future (Lucas *et al.* 2007) risk of smoke taint may also increase.

Current Options for Dealing with Climate Variability

Variability in temperature

Hot temperatures (>40°C) experienced during the growing season are managed by ensuring that the vineyards are kept well watered. For a vineyard to be protected from heat stress it may be necessary to begin watering up to three days before a forecast hot event. There is a limit to how much water can be applied to a vineyard however, especially post-veraison (colour change and berry softening), as juice dilution due to excessive swelling of the berries will impact on quality. Water stress post-veraison is essential for quality wine, though abundant water post-veraison is of less harm to the resulting berry quality than excessive water between flowering and veraison (McCarthy *et al.* 1992).

Windbreaks can be useful to protect the outside rows of a vineyard from hot, dry, northerly winds. They can impact negatively by housing birds (a pest problem), robbing vines of nutrients and water, and increasing the risk of frost by trapping of cold air around the vines.

Sudden hot snaps can result in sunburn on the skin of the berry. The impact of this is most severe after leaf plucking (a practice intended to optimise bunch exposure to sunlight). Wine grape purchase contracts penalize growers for this berry fault. Again, reliable forecasting can aid the timing of some viticultural operations.

Variability in the ripening of grapes due to cool or hot summers has been managed as a matter of course. Cool growing seasons can, in some cases, result in less than desirable ripening of the grapes. Volatilization of aroma compounds in warmer temperatures, or changes in the relative concentration of these compounds, may affect wine styles (Jackson and Lombard 1993). One of the interesting and intrinsic values of wine is the variation of the product from season-to-season, resulting in 'better vintages' and 'poorer vintages'. There is, in this regard, an inbuilt flexibility in the industry to adapt to climate variability in that it is already accepted by consumers that variation exists. Australia is known for its consistency in product though, especially in the UK. This consistency is maintained by varying sources of winegrape supply from year to year.

Most grape varieties can have various end uses, which facilitate adaptation to interannual temperature variability. Chardonnay grapes for instance, can be used in sparkling wine or a more full-bodied white table wine depending on the temperature of the growing season. The winemaker commonly blends wine from different regions, or different varieties, to take advantage of the complementary flavour profiles developed in the grapes.

Frost is presently managed by site selection, overhead sprinklers, helicopters (to create air movement and mixing), soil moisture maintenance (through irrigation), vine training systems (higher canopy), keeping soil surface cleaner (free of mulch), and foggers.

Variability in rainfall

In Australia most grape production occurs where the water requirement of vines is far higher than the quantity of water provided by rainfall. Irrigation has therefore been widely adopted in Australia. To manage water availability to the vines the majority of vineyards in Australia are equipped with soil moisture monitoring devices ranging from simple gypsum blocks, to neutron probes. In areas with salinity issues, computer controlled irrigation systems are used to increase efficiency while reducing the impact on the environment.

High rainfall in most areas results in lowering the frequency or rate of irrigation. High rainfall in areas where vigour may be a problem due to good soil fertility, or cooler growing conditions, has to be managed by canopy manipulations, or trellis design.

Low rainfall in summer has been managed by increased understanding of vineyard water requirement. More efficient watering strategies have been implemented, such as regulated deficit irrigation (Goodwin and Jerie 1992) and partial root-zone drying (Dry and Loveys 1998). Regulated deficit irrigation will ultimately lower yield by reducing berry size, while partial root-zone drying does not (Possingham 2002).

Rainfall impacts on disease incidence. This is important as grape purchase contracts have inbuilt penalties linked to various levels of disease. Pest and disease management in the current climate is dependent on a limited understanding of the ecology of Light Brown Apple Moth (LBAM) and long experiences with the fungi involved. LBAM affects vineyards by larvae physically damaging the developing grape berries predisposing them to Botrytis infection. Inundative releases of moth parasites have been trialled to control LBAM. Even without LBAM, rainfall up to and during harvest has the greatest impact on the crop with potential for crop losses due to Botrytis infection affecting the berries. Chemical control is expensive does not always provide effective control of Botrytis. Downy Mildew and Powdery Mildew, two other important fungal diseases, are adequately effectively controlled in most climates.

Adaptation Options for Dealing with Climate Change

Temperature increase

Suitability for growing different winegrape varieties will change in a warmer climate. Matching a variety of winegrape to a particular climate so that the winegrapes ripen at the optimal time in the harvest period is fundamental for the production of quality wine. Two main adaptation options exist for the viticulture industry to adapt to a warming climate: Either new sites can be selected for a particular variety to match the warmer climate; or ‘longer-season’ varieties than those presently planted can be established in existing sites.

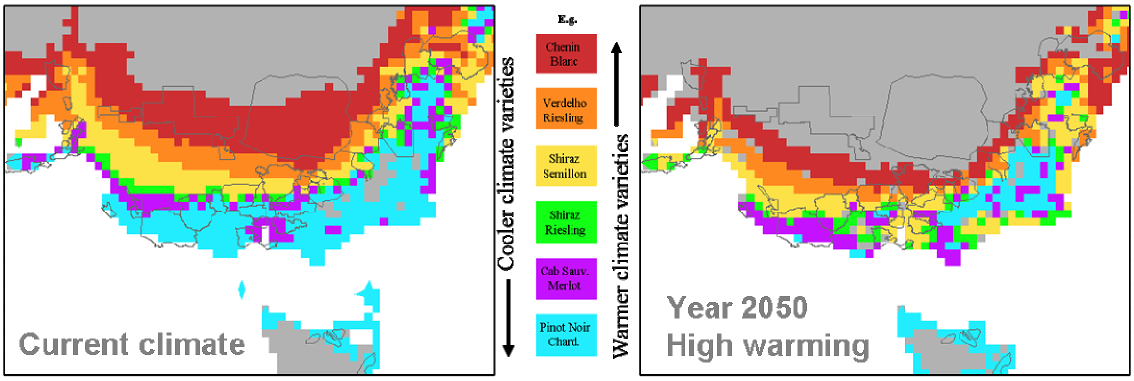

Figure 6.4: Projected shifting of grapevine growth suitability zones in South-eastern Australia under a high warming scenario in 2050 (best estimate) compared to current climate.

Change varieties of grapes grown in a region

To maintain consistency of quality wines, the industry can adapt to temperature increases by changing the varieties of grapes growing in different areas to match the likely future growing season profiles. Ripening can then coincide with the best possible climate conditions (Schultz 2000). In regions where the current climate is already considered warm to hot, however, replacing existing varieties with later ripening wine grape varieties that have market acceptance may not be possible with currently available varieties. Breeding of wine grape varieties that ripen later in the season and are able to maintain a good sugar to acid balance is one of the aims of the CSIRO vine breeding program (Clingeleffer 1985).

Removal of vines at some break-even costing to maintain phenological suitability could be practiced. The loss of production, and planting costs, can be weighed against quality loss, as the variety loses fitness for the particular climate. The rate of climate change will determine the rate of variety change. Vineyard life may decrease from the accepted 30 plus years.

The opportunities to manipulate phenology by cultural or chemical means are limited. In cases where demand for varieties has varied, top grafting of different varieties has been successful.

Australian wine law does not have variety restrictions built into it so there is greater adaptation potential than in Europe. Adaptation in Europe is restricted due to the Appellations Contrôlées system (France), and the Denominazione di Origine Controllata (Italy), for example. The wine law in these two countries allows for only certain grape varieties to be grown in certain regions for wines produced to be awarded the regional quality classification (Johnson 1989).

Change vine/vineyard locations

Calculation of potential areas available for viticulture in the future indicates that the potential area available in Australia for cool variety grape growing could be severely reduced. In fact, if the overall quality of grapes is to remain equivalent to that of the present day the area suitable for viticultural production may reduce by 40% by the year 2050 (Webb 2006) (Figure 6.4). The reduction in land area suitable for viticulture has also been found to reduce in the United States (White *et al.* 2006).

There is some potential for climate amelioration through exploitation of alternative sites within and surrounding existing vineyards. Variations in trellis structure can alleviate vigour problems created by some climatic factors. Use of mesoclimates has enabled vines to be grown in marginal areas by taking advantage of e.g. more direct solar radiation. In the selection of alternative sites, consideration of landscape (i.e. tree belts, valleys, north-facing slopes) will be necessary.

Within a region movement in elevation and aspect (Becker 1977), or complete relocation, to take advantage of future climate potential may be necessary (Jones *et al.* 2004; Kenny and Harrison 1992; Webb 2006). It may only be on the hot extremes where varieties become redundant, or new varieties will be required (Webb 2006).

Many factors other than temperature will need to be examined to assess the potential of new sites: soil type (Northcote 1977), water availability (McCarthy *et al.* 1992) and infrastructure. Neither the vines nor the infrastructure associated with them (trellising, wine processing and tourism facilities) can be moved on a year-to-year basis, limiting geographical flexibility.

Viticultural practices to affect timing of bud-break

If bud-break becomes uneven or protracted due to the chilling requirement of vines not being met, use of chemical dormancy breakers (Shulman *et al.* 1983), or other management treatments, e.g. evaporative cooling treatment (Nir *et al.* 1988) may offer some alternative adaptive measures.

Phenology will be difficult to influence *in situ*. However some potential exists to slightly delay bud break by delayed pruning bud. Dunn and Martin (2000) have manipulated the timing of budburst from shoots by delays in pruning (six-weeks) to push bud burst forward (buds burst about 4 days later). The use of some rootstock material may affect timing of budbreak (Dry 2007).

Risk assessment: sustainable industry in more marginal areas

The methodology of Kenny and Harrison (1992) in establishing criteria for identifying unacceptably high frequencies of extremes, and has been explored regarding viticulture suitability (Webb *et al.* 2007c), but this could be expanded with regard to water balance (drought/ flood/frost), or heat stress.

Winemaking adaptation and winery infrastructure

Wine making techniques could be developed whereby guiacol and other smoke taint compounds could be effectively removed. Similarly, alcohol levels in wine may need to be managed. Alcohol removal from wine is a costly process.

Cabernet Sauvignon currently finding a home in more premium lines of a wineries output (e.g. Penfolds Bin 707) may end up in a different product (e.g. Rawsons Retreat). This grape source change will occur gradually. Improved long range forecasting could help growers and winemakers finalize contracts depending on the expected climatic outcome of the season.

Winery capacity is built around expected winegrape intake. This infrastructure and has some flexibility in that more processing vats can be introduced. With more fruit coming into the winery over a shorter time-frame, pressure on crushing/pressing operations will also exist. Again, more, or larger capacity, units can be installed. These adaptations are not, however, without major cost penalties.

Carbon dioxide enrichment

Viticultural management adaptations to increased vegetative growth

Increasing trellis complexity, with a corresponding increase in cost of vineyard management, has been one way of managing increased vegetative growth in higher rainfall regions (Smart and Robinson

1991). This practice is used in some of the cooler/higher rainfall winegrape-growing regions where winegrape vine vigour can be a problem. The impact of an increase in within-canopy shading associated with enriched CO_2 conditions may necessitate the need for an increased number of passes of vine hedging equipment post-veraison. In warmer regions, these two adaptation options may be prohibitively expensive due to lower returns on the crop and a shortage of labour. Therefore other more cost effective growth management options may need to be explored.

Regulated deficit irrigation and more recently partial rootzone drying are water saving management practices that could be utilised to regulate vigour (Goodwin and Jerie 1992) and offset any growth enhancement from elevated CO_2. In most environments the aim is to increase water deficits post-flowering and pre-veraison to stop growth. Coordinated adjustment of irrigation scheduling and leaf area will be needed in response to CO_2 changes.

Adjust vine nutrition to address imbalance in carbon:nitrogen ratios

Should increasing CO_2 concentrations negatively impact fermentation through increases in C:N ratios in the winegrape juice then two possible adaptation options could be implemented. (Monk *et al.* 1986) found that by fertilizing vines (200kg nitrogen/ha) he produced juice with similar elevated fermentation properties to those where diammonium phosphate (an additive that increases the nitrogen content of winegrape-juice) was added.

Management to reduce the impact of increased yield variability

Flexibility in the winery with regard to processing capacity (tonnage) will be required if the projected increasing yield variability with increasing temperatures and CO_2 enrichment is realised (Bindi *et al.* 1996). Yields can already vary by over 30% from year to year (Dunn *et al.* 2004).

The study by Dunn *et al.* (2004) show that better yield regulation is possible, but this relies on: accurate yield forecasts to begin with; a quantitative understanding of yield compensation in response to regulation at different times throughout the season; and accurate methods to thin crops.

Supply of unwanted varieties and substandard quality winegrapes is currently being managed by a prohibitive pricing policy. If the supply became more variable the question is who wears the risk of extreme climate induced reductions in winegrape quality, the winegrape grower or the winery? An essential adaptation to climate change may be a fair policy to distribute the risk appropriately to each partner. Winegrape supply contracts are usually only for five to ten years. With forward planning, wineries can manipulate sourcing to allow for changes in temperature.

Water balance

Rainfall: short-term and longer-term forecasting

The scope of the impacts of lower rainfall depends on temperature, existing water sources, evaporative demand, competition for water supply from alternative industries, irrigation infrastructure, soil type, and timing of water shortages in the vine growth cycle. These factors can be incorporated into models which evaluate water balance and irrigation needs. If there is a need to allocate water more efficiently then the timing of water supply may have a large bearing on the yield and this will need to be understood in the context of future reduced rainfall. Cost and efficiency of holding dams, off-peak rates, and water quality will need to be explored.

Rain, or the threat of rain, may induce growers to pick early (to reduce risk of Botrytis and/or winegrape juice dilution) and provide immature winegrapes for processing (Jackson and Lombard, 1993). Climate change may result in a greater frequency of extreme rainfall events (CSIRO and BoM 2007). Short-term forecasting of such events at harvest time is crucial, and will become more so.

Water purchasing

Compared with some of the other water users in the Murray Darling Basin, grape growers have a low demand (average water application rates for main irrigated cultures in the Murray-Darling Basin: 3.0ML/ha for grapes, 8.2ML/ha for cotton, 12.9ML/ha for rice (http://audit.ea.gov.au/anra/atlas_home.cfm)). As a proportion of the value of the crop, the cost of water may not have as much impact for viticulture as it would for other industries, provided the industry can purchase the water it needs (NLWRA 2001).

Vineyard irrigation management

Increasing efficiencies in irrigation of vines can facilitate the management of limited water supplies. Regardless, it will be necessary to re-assess water resources and drought management in the context of future reduced rainfall. Applying saline water strategically may assist growers to cope with drought, though extreme caution would need to be applied with regard to effects on soil structure (Clark 2004).

Viticultural practices to address salinity

Development of salt tolerant rootstocks (Dry 2007) and better irrigation management (see above) may only partly overcome the problem of salinity. Salinity issues can also be addressed with existing management practices. Banrock Station (http://www.banrockstationwines.com/au), and many other vineyards use computer controlled irrigation scheduling to ensure that no water seeps into the water table. They control the volume of water in the soil profile by having soil moisture probes regulating the irrigation frequency and, consequently manage salt levels.

Water purification and recycling

Waste water from wineries, or large population centres, can be used on vineyards. Water recycling allows extra water to be directed to vineyards. Many vineyards (e.g. near Sunbury, near Ararat, and in McLaren Vale) utilize winery or town waste water already. With the demand for such water recycling likely to increase with climate change, there is a need to evaluate the long-term sustainability of this approach given the sometimes elevated levels of dissolved mineral salts in the water (Hermon *et al.* 2004; McCarthy and Downton 1981).

Management of the inter-row environment

Schultz (2000) explains that in Europe, shifts in precipitation patterns may necessitate introduction of cover crops between vine rows over winter in order to minimize soil erosion and to maximize water and nutrient storage. The future precipitation regime will have longer dry spells interrupted by heavier precipitation events (CSIRO and BoM 2007), increasing the need for both water conservation practices and also erosion control measures. Such measures could include the planting of inter-row ground-cover using ‘drought tolerant’ grass and legume species.

Understand the effect of increasing CO_2 on vine water requirements

Whether elevated atmospheric CO_2 concentration reduces whole-plant evapotranspiration depends on the effects on leaf area index (LAI) as well as on stomatal conductance (Drake *et al.* 1997). No savings in water can be expected where elevated CO_2 concentrations stimulate increases in LAI that offset decreases in stomatal conductance. This balance will need to be better understood for grapevines to determine future water requirements as above.

Pest and disease risk management

Grapevine disease is currently managed by canopy manipulation and with use of chemical pesticides/fungicides. Understanding the action of the fungus can reduce necessity for chemical input. Some disease modelling programmes (e.g. AusVit) (Ash 1992) have been developed to increase efficiency of management. Development of, and better-targeted application methods for, pesticides, increased knowledge of vine and pest dynamics and technological advances in machinery will be essential.

Successful adaptation of viticulture pest management to climate change will rely on having a quality Decision Support System, based on a quantitative understanding of the ecology of each pest. It will be important to avoid surprise outbreaks that can be very damaging to high-value crops. Biological models could be linked to Geographic Information Systems to provide nation-wide geographical scale outputs in real-time (Bob Sutherst, pers. comm). One question the industry would like to know about is under existing conditions what is the potential range of the Glassy Winged Sharp-shooter (Luck *et al*. 2002)?

The effect of increased temperature and CO_2 enrichment may change disease dynamics from the point of view of the pest. Host-pathogen interactions have been found to change in high CO_2 environments (Coakley *et al.* 1999). Adaptation will need to account for this.

Risks of Maladaptation

Winegrape varieties that ripen later than 'ideal' under current climate conditions, but with the overall 'best match' for future climate conditions will likely prove advantageous in the long term. However, this may incur opportunity costs earlier on as the variety will not be optimal for current conditions. Hence, some mix of strategies may be needed to defray this risk. A cost-benefit analysis for planting longer season varieties that incorporates projections of regional climate variability (Timbal and McAvaney 2001) could help avoid these problems.

Selecting more elevated sites is one measure that could be used to reduce temperatures in the vineyard. Many of the more elevated sites may have been used for forestry or have been uncleared in the present day. These sites may therefore have higher risks of bushfires, and access for fire-fighting may be deterred. For this reason, the more elevated sites may have a higher risk of exposure to bushfire smoke.

Costs and Benefits

Temperature increases

Vineyards usually have a life of at least 30 years, within the time scale in which significant changes to the climate are expected to occur. Therefore, planning for climate change impacts with regard to phenological matching of climates should start now.

Webb (2006) has performed an evaluation of climate risks at an industry level with regard to impact to winegrape quality. In this context, potential future suitable winegrape varieties for each growing region and potential future suitable sites for growing winegrape vines have been considered. Evaluation of threshold events to determine the risk of climate extremes is being addressed with consideration of different macroclimates and mesoclimates (Sadras, Pers comm.).

With careful planning, matching the variety to the climate to achieve the best quality wine over the life of a vineyard should be achievable. An alternative to this option is to bear the cost of replanting vineyards more frequently or top-working with more suitable varieties if trellis and rootstocks are still satisfactory.

CO_2 enrichment

Canopy management in an enriched CO_2 environment will need to be addressed. Cost effectiveness, and adaptability to mechanization will be important.

The nitrogen balance in grapevines in CO_2 enriched growing conditions has yet to be adequately described. We will benefit by understanding the effect on wine quality and yeast nutrition so as to be able to modify management practices.

Rainfall changes

It will be necessary to address both future water requirements and also water availability. Climate models, scaled down to a regional level, can be analysed and impact assessments made of the effect of climate change on water budgets in present and potential future vineyard sites. It will be necessary to continue improving irrigation technology. The effect of enriched CO_2 on water requirements will need to be better understood.

Effects on the risk of pest and diseases will need to be addressed region by region. ‘Regional scale’ humidity projections could be utilised in the context of future winegrape disease risk. CO_2 effects on disease have to be considered when addressing future disease risks.

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Knowledge Gaps and Priorities

Table 6.1: Summary of climate change adaptation options for the viticulture industry indicating whether the option 1) has already been assessed or is a remaining knowledge gap, 2) is highly feasible, 3) would be feasible / effective immediately, or 4) should be a high priority for research, assessment and implementation in developing adaptation strategies.

Adaptation options	Options already assessed	Options with high feasibility	Immediacy	Priority activities
Temperature increase				
Change varieties of winegrapes grown in a region	✓	✓	✓	✓
Assess new sites	✓	✓	✓	✓
Vineyard design strategies to ameliorate climate impacts	✓	✓	X	X
Chilling requirement analysis	X	✓	✓	✓
Consumer and product flexibility	✓	✓	X	X
CO2 enrichment				
Cultural management to increased growth	X	✓	✓	✓
CO_2 on vine water interactions	X	✓	✓	✓
Vine nutrition to address imbalance in C: N ratios	X	✓	X	X
Impact of the interaction of a temperature increase and CO_2 enrichment				
Cultural management to reduce variability	X	✓	✓	✓
Infrastructure adaptation for varying yields	✓	X	X / ✓	X
Economic and legal adaptations to manage the financial risk of yield variation	X	✓	X	X
Rainfall changes				
Water balance predictions (inc. extremes)	X	✓	✓	✓
Irrigation management to increase efficiency	✓	✓	✓	X / ✓
Water purification and recycling	X / ✓	✓	✓	✓
Management of the inter-row environment	X	✓	✓	✓
Pest and disease risk management	X	➨	X	X
Salinity				
Irrigation and cultural practices to address salinity	X	✓	✓	✓

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7: HORTICULTURE

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Key Messages:

- Site suitability may change for some horticultural crops. There may be a reduction in areas for growing stone- and pome-fruits requiring chilling, and an expansion in areas for growing sub-tropical crops.
- Sunburn, timing of crop stages, vegetable crop bolting (premature flowering), colouration effects, flowering and pollination timing and failure, and other quality and yield issues will need to be monitored.
- Varietal selection can be used to better match the crop to the new climate regime. Utilising existing variation or breeding new varieties can facilitate adaptation. Drought tolerant plants for amenity horticulture will be favoured in drier climates.
- Water demand will increase for most crops growing under warmer conditions. Changes in rainfall and evaporation are likely to reduce soil moisture and runoff in much of southern and eastern Australia. Increased water demand combined with reduced water supply poses significant challenges. Increasing water use efficiency practices will be paramount.
- CO_2 concentration will increase in the atmosphere but the net effect is crop specific. Elevated CO_2 can enhance photosynthesis and water use efficiency in some plants. More research will need to be undertaken to fully understand the impact on each crop.
- Pests and disease pressure may change. Decreasing rainfall and humidity may reduce fungal pressure, depending on the timing. Summer rain may increase in some regions (e.g. Northern NSW) favouring fungal growth. Flooding due to extreme rainfall events could benefit some soil borne pathogens. Cold season suppression of some pest species may be reduced. Higher temperatures can increase the activity of pests and diseases, and perhaps have a negative impact on the effectiveness of parasites and beneficial organisms.
- Consumers may require assistance to accept some changed quality of produce (colour changes). More of a range of tropical produce may become available. The cost of crops tends to rise during droughts, which are likely to occur more often.
- Integrating knowledge from agronomists, agrometeorologists, and farmers to assess and access the utility of short- and medium-term forecasts, and long-term climate projections to capture and evaluate relevant knowledge will enable risk assessments to be undertaken that include the social, economic and environmental costs and benefits of adaptation. We need research on adaptive governance, resilience and barriers to adaptation. Industry-wide strategic planning will assist the industry to manage these future changes effectively.

Introduction

The horticultural industry is extremely diverse in Australia, ranging from tropical fruits, vegetables and nuts to those with significant cold-temperature requirements. Horticultural industries produce high value products from small areas. The industries consequently have a high level of management input, often aimed at ameliorating climate risks (e.g. via irrigation). However, in many cases they retain considerable exposure to various climate-related risks.

In Australia, in the year 2005, the gross value of production from fruits and nuts (excluding winegrapes) was $A2.55billion, from vegetables, $A2.13billion and nursery $A768million (ABS 2005). Together these accounted for about 15% of the total gross value of agricultural production for that year. Key fruit species include bananas, apples, table-grapes, oranges, peaches, pears, plums, pineapples, apricots, mandarins and strawberries. Key vegetables include potatoes, tomatoes, lettuce, brassicas, beans, pumpkins, carrots, onions and peas. Other significant contributors to the horticultural sector include the floriculture industry and the turf industry (ABS, 2007).

The broad pattern of climate projections reported for Australia indicate likely rainfall reductions in the temperate and sub-tropical regions, while in the north little change is indicated for annual rainfall. Droughts and fires are likely to occur more often. Even where rainfall is projected to decrease, precipitation intensity is projected to increase with longer periods between rainfall events. Hailstorms may increase in the east and decrease in the south. Temperatures are projected to increase more in the central regions of the continent and less in the coastal areas (CSIRO and BoM 2007). Humidity is likely to decrease, and solar radiation is likely to increase in the south. This means, depending on where the crops are growing, the impact will be related to the regionally specific magnitude and direction of projected climate change.

Due to the diversity of the industry regarding plant species and their agronomic and botanical differences, impacts will be considered in three horticultural groupings: temperate and Mediterranean, sub-tropical, and tropical, represented by five separate climate categories that have been described by Hobbs and McIntyre (2005) (Table 7.1). These horticultural groups fall roughly into three distinct latitudinal zones (Figure 7.1).

Table 7.1: Horticulture group, major growing regions, major crops grown in the regions and the climatic zones populated by horticultural production in Australia.

Horticulture grouping	Region	Major vegetable crops grown	Other major horticultural crops grown	Climatic Zones (Hobbs and McIntyre 2005)
Temperate and Mediterranean	Tasmania, Victoria, South-west Western Australia and the Murray Darling Basin	Potatoes, onions, brassica, lettuce, tomatoes, carrots and pumpkins	Stone fruit, pome fruit, berries, citrus (oranges), table grapes, and nuts (almonds).	Temperate cool-season wet Mediterranean
Sub-tropical	Central NSW-to Bundaberg (Qld).	Tomatoes, potatoes, capsicum, brassica, beans, lettuce, pumpkin	Bananas, pineapples, avocados, citrus (mandarins), nuts, avocados, some stone fruit and strawberries in the elevated areas.	Sub-tropical moist
Tropical	Darwin and the Kimberley and Central and Far North Queensland	Cucumbers, melons, chillies, beans capsicum and tomatoes.	Mangoes, pineapples, bananas, avocados, coffee	Tropical warm-season wet Tropical warm-season moist

Figure 7.1: Major horticultural production regions in Australia 2001/2002 (ANRDL 2007).

Climate Change Impacts

Climate impacts

Temperate and Mediterranean horticulture

In the temperate and Mediterranean zones of Australia, in the southern part of the continent (Table 7.1), temperatures are projected to rise by 0.3ºC to 0.6ºC by 2030 and up to 2.5ºC to 3.0ºC by 2070. The best estimate (50th percentile) of rainfall change is that it is expected to reduce in the range 2% and 10% by 2030, and between 10% to 20% by 2070, most of the reduction being in the winter and spring periods. Diurnal temperature range may increase in southern Australia, so maximum temperatures are likely to rise faster than minimum temperatures. Humidity is expected to decrease and sunshine is expected to increase (CSIRO and BoM 2007).

For most vegetables grown in these regions, growth will be more rapid as temperatures increase, up to a threshold of 25°C (Krug 1997). In these areas where mean daily temperatures do not currently exceed 25°C during growing season, overall temperature change effects should not have deleterious effects, while they may be negative where growing season temperatures are currently higher (Peet and Wolfe 2000).

Higher temperatures tend to shorten the period of growth of individual crops. The opportunity to plant earlier in the season, or harvest later, will effectively extend the length of the growing season in the case of lettuce (Pearson *et al.* 1997; Wurr *et al.* 1996), french bean (Wurr *et al.* 2000), and tomato (Maltby 1995). With shorter phenological cycles, double cropping (plant another crop after harvesting the first in the same season) may become possible, e.g. with lettuce (Pearson *et al.* 1997).

A reduction in the requirement of transplanting seedlings may benefit some enterprises. Solanaceous vegetable crops are generally seeded in heated glasshouses and not transplanted into the field until the danger of frost is past (Peet and Wolfe 2000). These crops may be able to be direct seeded if frost risk reduces, and soil temperatures increase. Very heavy frosts (-5ºC and below) can damage broccoli, so future reduction in frost risk could allow earlier planting dates (Deuter 1995). On the other hand, the emergence of cauliflower could be affected in warm climates due to poor vernalisation if planted too late in a season (Wurr *et al.* 1995).

In some cases higher temperatures may not be beneficial. Warmer summer temperatures for Hayward kiwifruit are likely to increase vegetative growth at the expense of fruit growth and quality (Richardson *et al.* 2004). Kiwifruit budbreak is likely to occur later, reducing flower numbers and yield in warmer areas (Hall *et al.* 2001). Bolting (premature formation of the seed head/flowers) of some vegetables (e.g. lettuce, parsley, spinach and silverbeet (chard) increases in frequency with high temperatures (Dioguardi 1995). Lettuce tipburn, a browning of the inner leaf margins, occurs due to inadequate calcium distribution, combined with high daytime temperatures (>30ºC) (Dioguardi 1995). The practice of lifting onions and allowing them to cure in the field is only possible if temperatures do not exceed 30ºC. Temperatures in this range are projected to increase in frequency in future climates so alternative curing techniques for onion may become more common (Salvestrin 1995).

Temperatures above 27ºC can lead to poor pollen germination for tomato plants (Maltby 1995). Strawberry plants cease to fruit and commence runner production in late spring and summer as day length increases and temperatures exceed 28-30ºC on a regular basis (Morrison 1995). Heat stress is displayed in tomato plants grown at 35ºC (Riveroa *et al.* 2003). Sunburn of some vegetable and fruit crops will result from extremely hot days (Wand 2007). While small temperature increases are beneficial for cauliflower, higher temperatures increase the duration of the growing season for cauliflower, and reduce the curd quality possibly leading to crop failure (Olesen and Grevsen 1993). Warmer than average growing seasons can result in less than desirable ripening of some fruit. Reduced sugar content in fruit such as pea, strawberry and melon produced under warm nights is often attributed to increased night-time respiration, although it may be caused by the shorter period over which the fruit develops at high temperatures (Wien 1997).

Apples, a major perennial crop, are very likely to flower and reach maturity earlier, with possible increased fruit size (Austin *et al.* 2000) (if access to water does not change). However, production of anthocyanin, the pigment causing colouration of apples, is suppressed by high temperatures (Ewa Ubia *et al.* 2006).

Most deciduous fruit and nut trees need sufficient accumulated chilling, or vernalisation, to break winter dormancy (Coombs 1995; Hennessy and Clayton-Greene 1995). Inadequate chilling due to higher temperatures may result in prolonged dormancy or uneven dormancy break (Lavee and May 1997), leading to reduced fruit quality and yield. Hennessy and Clayton-Greene, (1995) found that warming in Australian fruit growing regions causes greater reduction in chilling at sites with a higher present mean temperature and/or a wider diurnal temperature range. At marginal sites, such as Manjimup (WA), Renmark (SA), Griffith (NSW), Stanthorpe (QLD) and Swan Hill (Vic), the percentage of years with enough chilling for pome fruit can be more than halved for a 1°C warming, or reduced to zero for a 2°C warming. At relatively cold sites such as Lenswood (SA), Orange (NSW), Tatura (Vic) and Grove (Tas.), there is enough chilling for stone fruit for a warming of up to 2°C (Figure 7.2).

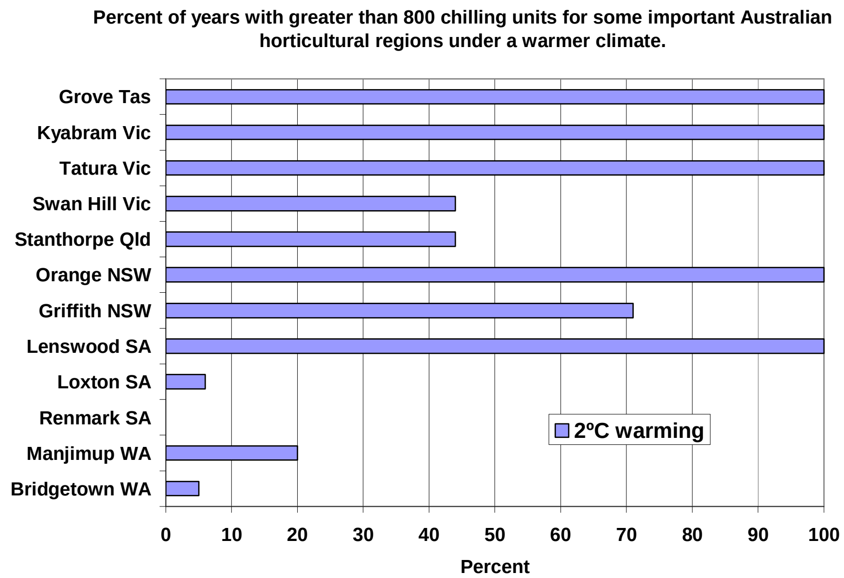

Figure 7.2: Projected change in the percent of year suitable for growing stone fruit as indicated by the reduction in chilling units in a future warmer climate. 100% of years in all described regions have greater than 800 CU in the current (1961-1990) climate.

The survival of pests that normally do not withstand cold winters is of some concern as this may result in additional threats to crops and the increased need for pesticides (Coakley *et al.* 1999). The Cabbage Moth (Diamondback moth) is a pest of worldwide significance wherever crops of Brassica (e.g. Broccoli) are grown. The pest is most destructive when an extended growing season occurs or where temperatures during the production season are high (Deuter 1995). With a warming climate the cabbage moth may have an increased impact.

Aurambout *et al.* (2006) reported that "A poleward shift in the geographical range of some pests and pathogens has been observed during the last century." Examples of this potential are demonstrated in a recent modelling analysis which indicated that if citrus canker had become established in Queensland, the geographical range of the pathogen, *Xanthomonas axonopodis pv. citri*, was predicted to extend further south with a 1-5ºC temperature increase (van Rijswijk *et al.* unpublished); and a predicted increase in winter temperatures may prolong the survival of weed hosts through winter increasing the ability of Sliverleaf Whitefly to overwinter (known as a "green bridge").

The economic impact of cost of control and yield losses for the Australian horticulture industries due to weeds have been estimated at $A19million (at least) (Sinden *et al.* 2004). Shifts in weed species will need to be monitored, since climate changes may allow tropical weed species to move further south, and changes in competitiveness may allow changed seed dispersal mechanisms. Ziska and Teasdale (2000) have shown that sustained stimulation of photosynthesis and growth of perennial weeds could occur as CO_2 increases, with a reduction in effectiveness of some chemical controls (e.g. glyphosate) and potential increases in weed/crop competition.

Generally, for the southern regions of Australia, rainfall is projected to decline (CSIRO and BoM 2007). Lower rainfall combined with more evaporation under climate change will result to decreased inflow into catchments (Cai and Cowan submitted; Hennessy *et al.* 2007; Jones and Durack 2005) and this means less water will be available for irrigation. This factor will have a major impact on the horticulture industry as these crops are generally irrigated whereby the availability of water tends to offset the climatic variations and allows produce to be supplied with a greater degree of regularity and security. However, as horticultural products tend to have higher value per unit water used than other agricultural products there is the likelihood of attracting the irrigation resource away from some broad-acre activities (NLWRA 2001), as occurred in 2006/07.

Severe water shortages can affect survival of some vine and tree crops, as has been observed with the 2006/7 drought (MDBC 2007), so overall vulnerability is greater than annual horticultural or cereal crops in these instances, as re-establishment is more costly.

Amenity horticulture and parks and gardens management will be required to adapt to drier conditions in future climates in southern Australia. In some cases e.g. in Perth, Western Australia, watering of gardens is currently restricted to twice per week, once only on each allocated day (see http://www.waterwisewaysforwa.com.au/go/secondary-navigation/what-are-my-watering-days). Drought tolerant plants, domestic water storage for gardens or grey water recycling can help with adaptation to watering demands.

Consequences of increased frequency and scale of extreme rainfall events for horticulture include flood damage, erosion damage and increase of disease pressure after such events. Recent floods in the Gippsland region (June, 2007), had a significant economic impact on the horticulture, dairy, timber and tourism industries in Gippsland. Some vegetable growers in the low lying river flats lost their entire planting and substantial amounts of top-soil. More than 1500 farms, over 100 businesses and more than 200 houses were significantly affected. Many communities that were hit by the flooding had already been in recovery mode from the effects of extended drought and recent bushfires. The Flood Recovery Ministerial Taskforce announced a recovery package totalling more than $60 million (Business Victoria 2007).

Hail damage can result in serious financial losses for apple and cherry growers (Urry 1995). Projections of changes in hail risk for the end of the century indicate an increase in large hail risk in eastern Victoria and along the coast of NSW. The large-hail risk for this region is projected to almost double, increasing by between 4 to 6 days per year (Abbs and Rafter 2007).

Frost incidence is expected to reduce in future, though with changes to phenology of some perennial crops, e.g. earlier budburst (Sparks *et al.* 2005), the frost risk may stay the same. In drought years, which are expected to occur more often (Mpelasoka *et al.* 2007) with drier soil and less cloud cover, tendency for frost increases.

Apple and pear scabs, and brown rot of stone fruit are the most important diseases of temperate deciduous fruit in Australia. High moisture levels assist their survival. Important vegetable diseases include Target spot (potato and tomato) and Verticillium wilt (tomato). There has been little analysis of the implication of these and many other diseases under climate change but with reduced growing season rainfall and humidity in southern regions pressure from these fungal pathogens may be reduced.

Sub-tropical horticulture

In the subtropical horticulture zone of Australia, the mid-eastern part of the continent (Table 7.1), temperatures are projected to rise by 0.6ºC to 1.5ºC by 2030 and 1.5ºC to 4.0ºC by 2070. Annual rainfall is projected to reduce in the range 2% to 5% by 2030 (50th percentile), and 5% to 20% by 2070 (50th percentile), though the 10th to 90th percentile uncertainty range is very large in the tropical regions by 2070. Diurnal temperature range is projected to decrease in the north of Australia, with minimum temperatures increasing faster than maximum temperatures, leading to a reduction in frost frequency (CSIRO and BoM 2007).

Over the past three decades in particular there have been substantial changes in frost characteristics. In eastern Queensland, there has been significant warming in May (reducing incidence of early frosts) and earlier date of the last frost suggesting a contraction in the frost period (McKeon *et al.* 1998). In a study of New South Wales and Queensland frost frequency (Stone *et al.* 1996) suggest a downward trend in numbers of frosts over the period of record (at the 95% confidence level) at six of the nine stations considered. With trends of increasing minimum temperatures projected to continue (CSIRO and BoM 2007), then there could be quite marked decreases in the length of the frost season over the next decades.

The benefits in reduction in frost incidence have been illustrated by expected increases in spatial distribution of areas suited climatically to optimum growth of two subtropical crops, avocado and pecan nut, in South Africa in future climates. Climate thresholds for optimum growth of these species were identified and modelled increases in suitability for growing these crops were found (Schulze and Kunz 1995).

Pineapples are extremely sensitive to both frost and temperatures higher than 32.2ºC. Hot dry westerly winds in the summer season can also cause severe losses. Planting in the coastal zone (within 40km of the coast north from Brisbane to Gympie) is undertaken to avoid frost. (Scott 1995). Projections of increasing (overall) wind speed for this region (of the order -2% to +7.5% by 2030) are projected (CSIRO and BoM 2007).

For citrus, winter temperatures in the range of 0ºC(min) to 14ºC(max) are required for the ‘resting period’ for bloom, so some of the warmer sites may become too warm for optimum production. A study over twenty-two sites in the US indicated that citrus plantings may shift slightly poleward in the southern states of America (Rosenzweig *et al.* 1996).

Excessively warm temperatures during the bloom or early fruit set period are also known to induce fruit abscission in citrus. Fruit quality, with respect to both development of sugars and colour, is also greatly influenced by temperature, with tree storage time decreased and rind re-greening increased as temperatures rise (Rosenzweig *et al.* 1996). High temperatures at flowering also adversely affect pollination of some sub-tropical crops, e.g. avocado (Schaffer *et al.* 2002).

Capsicum and chillies grow best when temperatures are between 20ºC and 30ºC. Temperatures above 30ºC can result in flower buds falling off and yield being affected, while temperatures below 15ºC are also not ideal. The red colour of ripening capsicums develops between 18ºC and 25ºC but if temperatures rise above 27ºC during the ripening a yellowish colour results (Murison 1995). Yellowing can also occur if tomatoes experience high temperatures when ripening (Maltby 1995).

After harvest, produce such as beans, melons and strawberries (important crop types grown in this region) are required to be cooled so as to remove field heat quickly (Coombs 1995), so with projected temperature rises, the costs and benefits of shifting harvest time to a cooler part of the day, or increased refrigeration expenses, will need to be assessed.

Pest impacts are widespread and costly (Queensland fruit fly and the light brown apple moth alone cost Australian horticulture and viticulture about $50M p.a.), and include major trade access issues for fruit fly host crops in particular (Sutherst *et al.* 2000). The pests, such as Queensland fruit fly (affecting all stone and pome fruit, citrus, tropical fruits, and some vegetable crops), heliothis moths (fruit, melons, vegetables), and diamond back moth (brassica vegetables) respond strongly to climate signals and their impacts are extremely dependent on climatic variability.

Increasing frequency in extreme rainfall events may lead to conditions favouring some root invading fungi, for example, the fungus *Phytophthora cinnamomi,* which affects avocado. Pressure from these type of organisms may need to be carefully monitored (Howden *et al.* 2006).

Tropical horticulture

In the tropical horticulture zone of Australia, the northern part of the continent (Table 7.1), temperatures are projected to rise by 0.6ºC to 1.5ºC by 2030 and 1.5ºC to 4.0ºC by 2070. Annual rainfall is projected to change in the range 2% wetter to 2% drier by 2030 (50th percentile), with some models projecting up to 40% wetter (or 20% drier) in the tropical regions by 2070 (10th and 90th percentile). Diurnal temperature range is projected to decrease in tropical Australia (CSIRO and BoM 2007).

As with sub-tropical horticulture, climate change may result in expansion of some of the horticulture industries suited to tropical climates. Mango, for instance, which was introduced into Australia in the mid to late 19th century (Beal 1976) is now commercially grown from the northern tropics through to subtropical regions of Australia (ABS 2007). Ninety percent of production comes from the cultivar Kensington Pride. If grown in the subtropics of Australia, where winter temperatures fall below 10ºC regularly, leaf yellowing occurs due to photoinhibition of the photosynthetic apparatus (Sukhvibul *et al.* 2000). This low temperature photoinhibition has also been reported for lychee and rambutan (Diczbalis and Menzel 1998) and banana (Musa spp.) (Damasco *et al.* 1997). In a warmer future climate, cold-induced photoinhibition will be reduced and greater agronomic potential would exist in some currently marginal areas.

Lady Finger bananas are more adapted to cooler conditions than Cavendish bananas. Cavendish bananas can have a 'muddy' appearance if grown in cooler conditions. Climate change may favour varietal trends away from the Lady Finger in current banana growing sites, or enable growth of Lady Finger varieties in sites previously too cool. Selection for new lines of Lady Finger more suited to warmer conditions can be part of a program to increase suitability of this variety. In a recent study it was found that Cavendish bananas grown in higher rainfall sites were firmer, and a deeper yellow colour was noted in bananas grown in cooler seasons (Bugaud *et al.* 2007).

Rockmelons (cantaloupes) are best grown in the dry tropics and inland irrigation areas as dews and wet conditions encourage fungal diseases (Coombs 1995). Timing of planting to ensure harvesting in the drier months may need to be shifted if projected rainfall patterns change.

Australian region studies indicate a likely increase in the proportion of tropical cyclones in the more intense categories, but a possible decrease in the total number of cyclones (CSIRO and BoM 2007). An example of the magnitude of the impact of a severe cyclone is demonstrated by the devastation caused by Tropical Cyclone Larry, on the 20 March 2006. The total cost due to all damage was $A351 million. Fortunately, the 1.75m storm surge occurred at low tide (BoM 2006; Queensland Government 2006). The significant damage to the banana industry has been calculated and the breakdown is presented in Table 7.2. There are approximately 12,500 hectares devoted to banana production in this area employing approximately 4000 people (1 worker per 3 hectares) directly. Many more are employed indirectly in the provision of supporting goods and services. Annual production for the cyclone affected area is approximately 17 million 13kg cartons with production costs estimated at $15 per carton (ABGC 2006).

Should an increasing percentage of rainfall come in heavy downpours then run-off containing fertilizers, pesticides, and animal wastes from agricultural activities would contribute to reducing water quality for downstream users. There may be increased risk of soil erosion in agricultural areas from the expected increase in the frequency of intense rainfall events (Cerri *et al.* 2007; Yu and Neil 1995). This will require improved soil surface management to reduce runoff rates (McKeon *et al.* 1988). In the tropical region the Great Barrier Reef is already seen as particularly vulnerable to climate change (Hennessy *et al.* 2007). The impact of runoff into these ecosystems after extreme rainfall events is exacerbated by fertiliser (Wooldridge *et al.* 2006) and regulation of runoff may become more intensely monitored in future.

Table 7.2: Cost of damage to the banana industry as a result of severe tropical cyclone Larry (Source: ABGC (2006)).

Banana crop losses in the cyclone affected regions have been estimated as follows:			
Region	% of crop lost	$value of crop lost	
Tully Valley and surrounds	95	$121m	
Innisfail and surrounds	95	$167m	
Atherton Tableland	80	$6.4m	
Kennedy & Murray Upper	50	$4m	
Combined value of crop losses for all regions		$298.4m	
The costs associated with the reestablishment or renovation of banana plantations in the cyclone affected regions has been estimated as follows:			
Repair type	Cost/hectare	# of total ha. For replant /renovation	Total replant/renovation cost across all farms
Replanting	$16,729	1,340	$22.4m
Renovating	$12,338	10,000	$123m
TOTAL			$145.4m

Carbon dioxide enrichment effects

Plant response to elevated CO_2 alone, without climate change, is positive. Recent studies confirm that the effects of elevated CO_2 on plant growth and yield will depend on photosynthetic pathway, species, growth stage and management regime, such as water and nitrogen (N) applications (Easterling *et al.* 2007). This variation in response is displayed when considering some studies involving horticultural crops. Wurr *et al.* (2000) found a null response of French bean to CO_2 enrichment in contrast to positive effects on onion (Daymond *et al.* 1997), beetroot and carrots (Wurr *et al.* 1998), avocado (Schaffer *et al.* 2002), citrus (Rosenzweig *et al.* 1996) and banana (Schaffer *et al.* 1996). Tree crops respond more than herbaceous crops to a CO_2 enriched environment (Ainsworth and Long 2005). Consideration of the effect of CO_2 enrichment crop by crop will be necessary to maximize benefits and minimize problems.

To assess the implications of these crop specific CO_2 effects, it will be necessary to relate the likely temperature change that will be associated with future elevated CO_2 concentrations. Temperature and precipitation changes in future decades will modify, and often limit, direct CO_2 effects on plants (Easterling *et al.* 2007). Some studies have been performed on horticulture crops where this effect is demonstrated. For instance, with lettuce, increasing CO_2 should increase yield, but this will be partially offset by warmer temperatures (Pearson *et al.* 1997). While Miglietta *et al.* (2000) found a positive effect of CO_2 on potato crop growth that may be counteracted by the effect of a temperature rise, depending on the initial temperature regimen, Rosenzweig *et al.* (1996) found minimal compensating effect of CO_2 on potato yields. Wurr *et al.* (1998) found carrots had a temperature optimum of about 15.8°C for maximum responsiveness to CO_2 enrichment.

Plants grown in elevated atmospheric carbon dioxide typically have lower protein and nitrogen concentrations (Drake *et al.* 1997; Morison and Lawlor 1999) though a recent review of many free air CO_2 enrichment (FACE) studies has reported these differences to be small (Ainsworth and Long 2005). Regardless, this may impact on the nutritive value of some vegetable crops and should be assessed.

An example of this effect can be seen in the case of the Colorado potato beetle (*Leptinotarsa decemlineata*), one of the most important worldwide pests of potato (though it is not found in Australia). Lower protein intake as a result of changed leaf composition (reduced C:N ratios) under enriched CO_2 environments decreases the growth rates of Colorado beetle larvae feeding on potato leaves. Reduced growth of the larvae may result in lower larvae reserves at the time of pupation, with possible negative consequences for the ability of the insect to survive winter conditions while diapausing into the soil (Hare 1990). This effect may interact with substantial increases in the potential distribution of the Colorado beetle as a result of higher temperatures alone (e.g. in the UK; (Baker and Allen 1993; Baker *et al.* 1998). The net outcome is uncertain.

Increasing concentrations of CO_2 may also improve water use efficiency in some instances (Grant *et al.* 2004; Morgan *et al.* 2004). Increased concentration of CO_2 in the atmosphere reduces stomatal conductance. If the reduced leaf conductance does not result in a very large increase in leaf temperature, which might increase the transpiration rate, then the smaller aperture would reduce transpiration (Boag *et al.* 1988; Kriedemann *et al.* 1976). Whether this affects water use efficiency of the whole crop depends on whether the increases in leaf area, caused by the increased growth in enriched carbon dioxide environments, counteract the effect of reduced stomatal conductance (Drake *et al.* 1997; Rosenberg *et al.* 1990).

Adaptation Options

Current Options for Dealing with Climate Variability

<u>Site selection</u>

Site selection to avoid unsuitable climate factors is practiced as a matter of course in horticulture. For all horticultural crops temperature is the main climatic factor which determines where and when crops are grown, and also has a significant influence on crop performance (i.e. time to harvest, product quality, and to a less extent, yield). For example, pineapples are only grown in a narrow coastal band of the continent to prevent injury to this extremely frost-susceptible crop (Scott 1995), and sweet corn is grown in Victoria only in the summer, and in north Queensland only in the winter. Avoiding planting some crops in seasons, or areas, likely to experience ‘above threshold’ temperatures can minimise risk. For example temperatures of greater than 30ºC could be avoided in the case of lettuce to reduce chances of lettuce tipburn (Dioguardi 1995).

A very early study showed that a 2°C warming may extend the range of citrus and subtropical crops to latitude 40°S in New Zealand (Salinger 1988). In the latter part of the last century, a coffee industry was established in far North Queensland near Kuranda. This industry was severely affected by frost in 1901, and during the ensuing decade recurrent frosts wiped out the industry (Mann, 1961). The industry began expanding again in 1980. Similarly, the citrus industry in Emerald in Central Queensland was established in the 1980’s and 1990’s following a significant increase in winter temperatures as compared with the 1960’s (P. Deuter, Pers. Comm.).

<u>Crop management</u>

Variability in the ripening of fruit and vegetables due to seasonal temperature variability has long been managed as a matter of course. Timing of production techniques, such as sowing, planting, fertilizing, irrigation, and using protective covers can be adapted to manage climate variability (Krug 1997). Earlier production in some years is possible due to decreased frosts (Peet and Wolfe 2000), however depending on the region, higher temperatures can shorten the growth of some individual crops and extend the season of production in others. Varietal selection is practiced as a matter of course to match harvest timing and daylength requirements e.g. strawberries (Morrison 1995).

Climate-ameliorating measures used to reduce sunburn include evaporative cooling, Surround® WP (a kaolin based coating also used as a pest repellent (Thomas, Muller *et al.* 2004)), and shade net (Wand 2007). Shade nets have the ability to prevent hail damage as well. A recent study assessed transparent compared to black shade net and found that temperatures and sunburn were reduced in the apple crop tested, though fruit colour was reduced under the black net, and the expense uneconomic compared with paying for hail insurance (in Spain) (Iglesias and Alegre 2006). Hail netting is very cost effective in the Granite Belt region of Qld to protect apples from hail damage – extensive areas of netting have been erected over new high density plantings over the past 20 years (P. Deuter, Pers. comm.).

Celery (*Apium graveolens* L. var. *dulce (Mill)* Pers.) is a biennial vegetable and requires a cold period to produce seed the following season (Pressman 1997). Timing of transplantation (Morgan 1995) can be adapted to reduce the impact of the warmer field conditions. 'Warmer than average' temperatures can cause premature bolting (flower formation) with celery production. To avoid this celery production is confined to the highland areas of southern Queensland (where bolting can still occur in a warm winter/spring period) and to southern states (P. Deuter, Pers. comm.).

Varying crop selections incorporates some natural resistance to heat stress. Experience suggests that crops with extended potential flowering periods are less sensitive to periods of heat stress compared with those that have more tightly determined flowering times. It has been suggested that indeterminate crops like peas and pumpkin, are less sensitive to periods of heat stress because time of flowering is extended compared with determinate crops like cauliflower and broccoli (Peet and Wolfe 2000). Selecting less risky periods or microclimates for planting the more susceptible crop reduces negative impacts.

With regard to adapting to inadequate chilling, chemical treatments are currently used to induce budbreak in some maritime or subtropical environments. Use of Dormex (Hydrogen cyanamide) as a way to promote budburst is becoming more common in perennial fruit growing operations (George and Nissen 1990). Other management approaches have been used including evaporative cooling by water sprinkling, high temperature treatment, late autumn application of nitrogen and irrigation. Kiwi fruit is an example of a crop that requires winter chilling for adequate bud break and flowering. An increase in warm winters has led to a decline in kiwifruit in the North Island of New Zealand, with a halving of the area planted in the period 1994-2000. Use of HiCane (a product containing Hydrogen cyanamide) and organically acceptable alternatives are being evaluated in New Zealand for use on kiwifruit crops.

<u>Varietal selection</u>

Intervarietal variation in chilling requirement is utilized with some stone and pome fruit (e.g. Golden Queen Peach (Atkins and Morgan 1990)) and kiwi fruit varieties (e.g. Zespri Gold kiwi fruit) (Kenny 2001) to reduce the risk of poor dormancy break.

Cultivar selection and planting dates are directed toward either suppressing flower initiation, in the case of celery, onion or cabbage, or delaying it in the case of broccoli and cauliflower, until the seedling is big enough to support formation of a large head. Many vegetable growers base planting dates on soil temperature conditions, which automatically allows the adaptation to climate variability to occur.

Breeding varieties more adapted to high temperatures can reduce quality concerns with regard to lettuce (Wurr *et al.* 1996), and yield concerns with peas (Olesen *et al.* 1993) and potatoes (Manrique and Bartholomew 1991). Growing slow bolting cultivars of lettuce can reduce losses due to this problem (Coombs 1995).

Water management

In Australia, most horticultural production occurs where the water requirement of crops is far higher than that provided by effective rainfall (rainfall minus evaporation). Irrigation has become widely adopted in Australia so that yield and quality can be maximised, and so that the development phases of crops can be better predicted (giving more surety of harvest dates to maximise the marketing plans of growers). A large percentage of horticultural enterprises in Australia are equipped with soil moisture monitoring devices ranging from simple gypsum blocks to neutron probes. These enable improved efficiency in water use.

In areas with salinity issues, computer controlled irrigation systems are also used to reduce the impact on the environment. Lining the base and sides of irrigation channels, and covering the top of irrigation channels, is proposed for the Wimmera region of north-east Victoria. Supplying irrigation water in pipes can reduce losses. Many vegetable growers are adopting drip irrigation technologies providing significant water-use efficiencies, especially when compared to furrow or 'big gun' irrigation systems.

Watering to reduce heat stress and to manage frosts does alleviate some extreme conditions.

Low rainfall during harvest (and to some extent during other development phases of many horticultural crops) is a real advantage as disease pressure is reduced. Horticultural growers select the most favourable locations for production based on a number of factors, and high rainfall during harvest one factor that is avoided.

Flooding is managed by avoiding risky sites, such as floodplains, or ensuring adequate drainage is maintained. Increased understanding of crop water requirement, and employing increasingly more efficient irrigation practices have been used to manage low rainfall in summer.

Hail netting is becoming increasingly introduced for higher value crops like cherries (Coombs 1995).

Pests and diseases

Climate variability also affects pest and disease incidence. Pesticides are increasingly used along with both cultural practices and biological control methods. However, pesticides are expensive and not always effective whilst integrated management of horticultural pests in relation to current climatic variability depends on effective monitoring and predictive systems. For example, a Black Spot warning service operates in the Granite Belt of South East Queensland. This fee-for-service bulletin provides weekly updates on occurrence of pests and diseases of apples. It also provides advice to apple growers of potential incursions of the major pest and diseases (Codling Moth and Black Spot). This advice is based on degree days and leaf wetness models and allows for targeted and timely application of pesticides/fungicides (Peter Nimmo, Pers. Comm).

Current management practices that respond to, or override, climatic variability include:

- Importation of exotic natural enemies of pests that were previously introduced without them. Also repeated, mass (inundative) releases of parasitic wasps to control insect pests.
- Cultural practices such as mixed crops, crop free production, or use of physical barriers to reduce disease transmission.
- Biosecurity and good hygiene in orchards.
- Chemical pesticides and increasing bio-pesticides (e.g. Bt).
- Monitoring and use of predictive models to improve timing of interventions to coincide with high-risk periods.
- Landscape scale-management involving groups of growers cooperating to reduce communal threats.
- Monitoring and mating disruption using insect pheromones.
- Automated weather stations that incorporate simple simulation models to warn growers when the risks of particular pests or diseases are rising.

<u>Consumer behaviour</u>

Availability of most horticultural crops, e.g. strawberries, will tend to increase throughout the year. Availability of some crops may be reduced in some seasons. If production becomes more difficult due to the effects of higher temperatures or droughts or other climatic events, then consumers pay higher prices to Australian growers or for an imported product. Banana prices increased dramatically after severe tropical cyclone devastated the crop in 2006.

<u>Integrating knowledge: Seasonal forecasts</u>

Fruit and vegetable growth and quality are very sensitive to extremes of weather such as very high temperature, severe frost and persistent drought. Consequently, some producers are now considering crop selection based on seasonal forecasting predictions. The possibility of using such forecasts to enable progressive adaptation to climate change was first raised by McKeon and Howden (1992). Seasonal forecasts are routinely produced now for both rainfall and temperature. Their use in other agricultural production systems and decision-support has been well-explored. For example, peanut processing and marketing bodies profitably use forecasts of likely production to adjust their operations strategically (Meinke and Hammer 1997). Horticultural industries' requirements for seasonal temperature (and rainfall) forecasting information, is wide and varied (a large number of commodities and cropping systems, spread over a very wide range of climatic regions) (P. Deuter, Pers. Comm).

Adaptation Options for Dealing with Climate Change

<u>Site selection</u>

In future, this practice of carefully selecting appropriate sites will be maintained. Consideration of the changing climate should be made when selecting perennial varieties and where these should be planted. Identification of threshold temperatures or other climate conditions for crops, spatially represented for a range of future climates, can expose risky, or less risky, areas. In the cooler regions of Australia some spatial studies have been performed (Hood *et al.* 2002) and are being undertaken (Sposito 2007). There may also be landscape design/locations (i.e. tree belts, valley location) that may enable amelioration of warmer conditions. This type of analysis could be extended to yield or profitability expectations.

Growers of frost-sensitive fruit may consider planting in regions once considered unsuitable due to frost risk. Studies have shown an expansion of areas across the Mediterranean region of Europe suitable for growth of tropical and sub-tropical crops such as citrus, avocados and bananas (Houerou *et al.* 1992) and similarly in Southern Africa for avocados and pecan nuts (Schulze and Kunz 1995). A similar trend is likely for Australia though this modelling has not yet been performed for sub-tropical regions of Australia.

<u>Crop Management</u>

Fruit and vegetable growth and quality are very sensitive to extremes of weather such as very high temperature, severe frost and persistent drought. However, the amount of damage suffered often depends on the development stage reached when the extreme conditions occur and this phenological information needs to be incorporated into adaptation strategies. Understanding when the likelihood of extremely hot days (e.g. daily maximum temperature above 35°C) may occur, along side projected phenological timing, can inform risk assessments.

Pears/peaches/cherries require matching of cross-pollinating varieties for fertilization (Baxter 1997). If all varieties of cross pollinators are not phenologically affected in the same way then there may be a need to take action to ensure future flowering synchronization. Similarly, adaptation will be required to manage the variability and protracted full bloom of pip, stone fruit and nut trees if dormancy is affected, leading to non-uniform budburst (Atkins and Morgan 1990) e.g. pesticides with longer residual action, harvest and marketing implications and other management practices extended.

Cherries are particularly sensitive to solar radiation. The production of quality fruit can be severely limited even by short periods (1-2 weeks) of increased radiation at critical times in their growth and development. Radiation is projected to increase in the spring months (CSIRO and BoM 2007) so possible shading protection, that would also offer hail and bird protection (often used in cherry growing) may be warranted (Iglesias and Alegre 2006).

Modelling of crop yields of almonds, table grapes, oranges, walnuts and avocados resulted in reductions to future yields due to climate change (if no adaptation implemented) (Lobell *et al.* 2006). All climate scenario experiments for vining peas showed that the duration from sowing to harvest is reduced for a given variety and that seed yields decrease relative to the original climate (Olesen *et al.* 1993). This yield decrease may be compensated for by earlier sowings. Where crops mature more rapidly, if yield is not affected, it may be necessary to plant smaller areas of crop more frequently in an attempt to smooth out supply functions e.g. cauliflower (Olesen and Grevsen 1993).

Timing of planting will be changed for some crops. Autumn soil temperatures could become too high in some areas for good germination of celery (Peet and Wolfe 2000). For potatoes, planting later in the season to avoid the very hot temperatures may be compromised by the shorter day lengths later in the year. These may have a negative impact on yield (Rosenzweig *et al.* 1996). Thus, any change in sowing needs to be accompanied by changes in day length requirements.

<u>Varietal selection</u>

In some cases, long season varieties will benefit from climate change more than short season varieties, e.g. onion (Daymond *et al.* 1997), due to the hastened progression through phenological (developmental) stages. The winter lettuce and brassica season (mid-April to October) in south-east Queensland will be shortened by several weeks to a month by 2030 without a change to more adaptable cultivars (P. Deuter, Pers. comm.).

Breeding of heat tolerant, low chill, and more adaptable varieties of various horticultural crops must begin. In the case of perennial fruit crops, consideration of canopy structure could be exploited whereby structures with natural self-shading ability could be selected. Product quality given growth under enhanced CO_2 and elevated temperatures will need to be evaluated and considered in breeding programs.

Water

The significant implications of climate change for water resources in the southern catchments (Cai and Cowan submitted; Hennessy *et al.* 2007), the adoption of water trading and the allocation of water for environmental flows mean that future horticultural production will not be independent of the futures of other industries. Water shortages would sharpen competition among various users of water, especially where large diversions are made for economic purposes. Furthermore, there is a 50% chance by 2020 of the average salinity of the lower Murray River exceeding the 800 EC threshold set for desirable drinking and irrigation water (MDBMC 1999).

Rural communities, businesses and their representatives must assess the strength of current planning and policies dealing with climate change and agriculture. To do so, the effects of climate change need to be fully understood throughout the community in terms of industry, economic, social and landscape change. A sustainable groundwater management plan (in years of poor river flow or high rainfall years) will be necessary. In addition there is an increasing emphasis on using reclaimed wastewater for agricultural/horticultural enterprises.

Changing levels of CO_2

A key adaptation to engage in now may be to invest some research effort into identifying plant characteristics that will be responsive to projected changes, incorporating them into breeding programs so that genetic variation in these characteristics is maximised and maintained in breeding programs for recombination to take place (Richards 2002).

Additional fertiliser applications may be required to maintain product quality (Monk *et al.* 1986) but noting that this may increase greenhouse gas emissions as well as having a range of other impacts. Costs of increased use of fertilizers, pesticides (including herbicides) will need to be assessed so that plant productivity could be sustained.

Certain weeds are also likely to benefit from higher levels of carbon dioxide, thus necessitating increased application of herbicides, which may lead to other environmental impacts. Tolerance to herbicides in increased CO_2 is one of many issues that needs to be examined.

Pest and disease management and risk

Under climate change it will be important to have better Decision Support Systems based on a sound understanding of the ecology of each pest to avoid surprise outbreaks. In particular, models should be developed to explain over-wintering of a wide range of insect pests and plant diseases, and changes in the timing and severity of pest populations. Pest/insect models usually base diapause on 7.5-10ºC i.e. over wintering occurs when temperatures are below this level. Increased winter temperatures mean these levels may not be reached in some regions resulting in impacts to intervention measures used for control. Adaptations to the changes in the risk of pest and diseases will need to be addressed area by area.

Both fruit and vegetable production still rely heavily on chemical pesticides despite recent attempts to improve the information available to guide better decision-making using climate-driven models and the wide-spread adoption of IPM systems. Strengthened efforts on the use of bio-pesticides and natural enemies will help to prevent crop damage, but they also demand support from better information systems. Biological models could be linked into GIS so the results are applicable around the country (i.e. geographical scale outputs in real-time).

In some cases the disease risks may decline but that in others they may increase. Assessments of changes in the potential distribution of a range of horticultural pests and diseases, in conjunction with exploration of adaptation options for managing the changed risks, will be required. CO_2 effects on disease have to be considered when addressing future disease risks.

Consumer impacts

Vegetables such as turnip or swede may suffer from consumer neglect, as more exotic vegetables may become more available/ affordable. For example, durian and other tropical crops may be able to be grown. Hence, a key adaptation may be marketing responses.

Colour of produce could be impacted with some of the possible aesthetic impacts identified being re-greening of oranges, and yellowing of tomatoes and capsicums. Increasing consumer awareness is currently undertaken in supermarkets and green-grocery stores in ongoing marketing programmes e.g. ZESPRI™ GOLD Kiwifruit (http://www.zesprikiwi.com/goldkiwi.htm).

Prices paid for produce may change. As food prices increase, so will imports of cheaper products, until such time as Australians ‘want’ to consume Australian grown, or supply of imports is reduced by other factors such as increased costs or increased demand form consumers in the exporting country – this will happen in China within the next 5 years (P. Deuter, Pers. Comm.). A review of the third assessment report which assessed the consequences of climate change for food and forest resources found that a global temperature rise of greater than 2.5ºC is likely to reverse the trend of falling real food prices that would be occurring to that point (Easterling and Apps 2005).

Integrating relevant networks and past experience to select best adaptation options

Climate science can provide insights into climatic processes, agricultural systems science can translate these insights into management options and rural sociologists can help determine the options that are most feasible or desirable from a socio-economic perspective. Any scientific breakthroughs in climate forecasting capabilities are much more likely to have an immediate and positive impact if they are conducted and delivered within a framework that includes: farmers, climate scientists, agrometeorologists and rural sociologists (Meinke and Stone 2005; Salinger *et al.* 2005).

The improvement in seasonal forecasts in the past decade and the anticipated improvement in the future will ensure that they remain pertinent under changed climatic regimes. However, whilst such forecasts are linked to production outcomes using cereal crop and grazing models, to date such strong analytical linkages have not been developed for the fruit and vegetable growing industries. Nevertheless, the use of forecast accumulated heat units to model crop development and compare information with forecasts of extreme weather occurrence offers great potential for management for horticultural industries.

Economic analysis of the costs of climatic drivers like ‘El Nino’ have been carried out for Ecuador where small farmers were shown to be most vulnerable (Vos and de Labastida 1999) and the cost of the drought in Australia (Adams *et al.* 2002) where the impact on different geographic sectors was analysed. Measuring costs of adaptation, or mal-adaptation, will be instructive for this industry.

Risks of Maladaptation

Fruit and vegetable production and marketing are very closely linked. A mismatch resulting in oversupply and undersupply has a dramatic effect on prices paid to growers. Therefore any adaptation strategies which result in changes to production timing and location will have consequences for the supply and demand chain. If they significantly change the timing and amount of product being supplied, over or undersupply can result, with consequent effects on both producer and consumer.

Drought relief packages for growing of crops not suited to an area could be considered a maladaptation cost. Average production by rural industries fell about 10 per cent due to the 1991-1995 drought, resulting in possible $5 billion cost to the Australian economy, with $590 million drought relief provided by the Commonwealth Government between September 1992 and December 1995 (BoM 2007). Droughts may become more frequent and severe in future climates (Mpelasoka *et al.* 2007; Nicholls 2004).

Costs and Benefits

Temperature

Fruit orchards have a life of 20-60+ years. Current plantings will be producing in the climate we are predicting to be warmer due to climate changes. Planning with regard to phenological matching of climates should begin immediately to avoid mismatching of varieties in a warmer climate.

It will be necessary to validate climate indices that describe current horticultural enterprises with regard to phenology of desired varieties. Once this is established it will be necessary to incorporate climate projections in models of crop growth. In this context, prediction of potential suitable crops for each region, or potential suitable sites for particular crops, can be considered. Determination of the risk of climate extremes can be addressed at the same time with consideration of different macroclimates and mesoclimates. Managing the risks of damaging temperature threshold events will provide substantial benefits.

Rainfall changes

To manage the risks associated with reduced water supply and increases in water demand it will be necessary to develop suitable models. Regional or local climate projections can be used as input to catchment-scale run-off models to assess the effect on water budgets in present and future potential production sites so as to identify adaptations needed. It will be necessary to continue improvements in irrigation technology. The effect of enriched CO_2 on water crop water-use will need to be better understood when looking at the water requirements for horticultural crops.

Adaptations to the changes in the risk of pest and diseases will need to be addressed area by area.

CO_2 enrichment

Canopy management in an enriched CO_2 environment will need to be addressed. Cost effectiveness, and adaptability to mechanization will be important. The nitrogen balance in CO_2 enriched growing conditions has yet to be adequately described. In addition, we need to consider the effect of CO_2 enrichment crop by crop to maximize benefits and minimize problems. CO_2 effects on disease have also to be considered when addressing future disease risks.

Additional costs to farmers to take advantage of possible benefits from increased levels of carbon dioxide will need to be considered. These costs could include increased use of fertilizers, pesticides, and herbicides so that plant productivity could be sustained. Energy costs (heating for glass houses) and the cost of maintaining the desired CO_2 levels in the glasshouse atmosphere are likely to decrease. Research into the effect of increasing atmospheric CO_2 on the nutritional quality of horticultural crops has been infrequently undertaken to date. If yields will rise with increasing CO_2 there is scope for improvements in the efficiency of photosynthesis and water use. This, however, requires more research on an up-scaled ‘canopy’ level.

Knowledge Gaps and Priorities

Table 7.3: Summary of climate change adaptation options for the horticulture industries indicating whether the option 1) has already been assessed or is a remaining knowledge gap, 2) is highly feasible, 3) would be feasible / effective immediately, or 4) should be a high priority for research, assessment and implementation in developing adaptation strategies.

Adaptation options	Options already assessed	Options with high feasibility	Immediacy	Priority activities
Temperature increase				
Re-assess location in regional terms.	X	✓	✓	✓
Link climate change and quality issues.	X	✓	✓	✓
Change crop production schedules to align with new climate projections.	X	✓	X	X
Decreased reliance on glasshouses.	X	✓	X	X
Invest in biotechnology and conventional breeding	X	✓	✓	✓
Use seasonal forecasts	✓	✓	✓	✓
Develop markets for new crops.	X	✓	X	X
CO_2				
Ascertain the effect crop by crop.	X	✓	✓	✓
Cost of production changes (e.g. savings in glasshouse management).	X	✓	X	X
Rainfall				
Integrated catchment management.	X	✓	✓	✓
Irrigation management to increase efficiency.	✓	✓	✓	X
Implement water trading in conjunction with water efficiency initiatives.	✓	✓	✓	X
Pests and diseases				
Integrated pest and disease risk management: varies from area to area.	X	✓	✓	✓

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8: FORESTRY

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Key Messages:

- Australia's native forests, which cover about 164 million hectares, include more than two thousand tree species many of which are highly vulnerable to climate change because of their narrow climatic ranges.
- Australia's plantation forests are dominated by *Pinus radiata* (radiata pine) and *Eucalyptus globulus* subsp. *globulus* (blue gum), which together account for about 69 per cent of the total plantation area. As both are grown over relatively wide climatic ranges, they should not be highly vulnerable to climate change in the short to medium term.
- Bioclimatic analysis can identify plantations that currently experience particularly hot and/or dry conditions. These sites could be monitored to provide an early warning if conditions become unsuitable for particular species in particular regions.
- At the same time, plantation productivity may be increased by rising levels of atmospheric carbon dioxide, but may be reduced by temperature changes, especially in conjunction with greater water loss at higher temperature or if rainfall is reduced. There are also potential problems due to increased risks from pests and diseases and potentially more frequent and more severe bushfires.
- There is an urgent need to improve the understanding of the effects of increased levels of atmospheric carbon dioxide and changes in temperature and rainfall on tree growth. It is particularly important to assess whether growth rates of particular species are likely to be increased or decreased at particular sites and how trees respond to stress through particular combinations of climatic changes.

Introduction

Forestry involves the study and management of forests and plantations for a wide range of commercial and environmental values, including wood production, watershed protection, biodiversity conservation and carbon sequestration. Forestry may be best considered as a continuum with native forests at one extreme and large-scale industrial plantations at the other (Donaldson and Pritchard 2000). Farm forestry refers to the management of trees in stands or woodlots for traditional wood products, as well as providing other benefits such as shade, nature conservation and dryland salinity amelioration (Abel *et al*. 1997). Both forestry and farm forestry can involve management of native stands, but apart from some brief background information on native forests, this review concentrates mainly on plantations.

The formal definition of forests refers to vegetation of a mature or potentially mature height exceeding two metres with an existing or potential crown cover of 20% or more. There are 164 million hectares of forest in Australia, but only about 7% of that area is native forest managed for timber production, and only about 1% is plantation forest. Though there are only about 1.8 million hectares of commercial plantations, these produce 62% of logs harvested from all forests. Farm forestry involves plantations of less than 1000 hectares under single ownership and accounts for about 20% of plantations. It is growing in importance and about a third of farm forest plantations have been planted since 1995 (National Forest Inventory 2007a). About 92 million hectares of the 164 million hectares of forests are woodland areas, where extensive grazing rather than wood production is the primary economic activity.

Native forests, including woodlands, form an important component of many farms. Climate change will place many unmanaged native forests at risk. Australian forests include many hundreds of different tree species. Many of these species have comparatively limited distributions and hence occupy narrow climatic ranges. For example, a 2.5^{o}C rise in mean annual temperature would result in about half of Australia's approximately 800 eucalypt species having their entire distributions shifted to be outside their current climatic range (Hughes *et al.* 1996; Kirschbaum 2000). This does not mean that eucalypts or other forest species growing outside their current climatic ranges would necessarily all die, but it is likely that they may well be at greater risk of extinction (Booth 2007). Climate change will also pose problems for plantation forests, but it will be possible for plantation managers to plant different species that are better adapted to changing climatic conditions if this becomes necessary.

Hennessy *et al.* (2007) have reviewed the likely effects of climate change on Australia and New Zealand for the Intergovernmental Panel on Climate Change (IPCC). They suggested that "productivity of exotic softwoods and native hardwood plantations are likely to be increased by CO_2 fertilisation effects, although the amount of increase will be limited by projected increases in temperature, changes in rainfall and by feedbacks such as nutrient cycling". Where tree growth is not water-limited, warming could additionally expand the length of the growing season in southern Australia, but they also cautioned that increased pest, disease and fire damage may negate some gains so that productivity declines are also a possibility. It is important to recognise that climatic and atmospheric changes are likely to have both positive and negative impacts on forestry, which we describe in further detail in the following sections.

Australia had about 1.8 million hectares of plantations in 2006. Of those, about 44% were hardwood and 56% softwood species (National Forest Inventory 2007b). Of the hardwood plantations, 61% were *Eucalyptus globulus* spp. *globulus* (blue gum) while 75% of the softwood plantations were planted with *P. radiata* (radiata pine). Figure 8.1 shows how hardwood plantations have increased in size in recent years while the area of softwood plantations has remained stable. *E. globulus* is grown mainly for paper products, while *P. radiata* is grown mainly for sawn timber, posts and poles, with residues being used for paper, particle board and other panels. Both *E. globulus* and *P. radiata* are grown in temperate parts of Australia. *Eucalyptus grandis* (flooded gum) and *Eucalyptus dunnii* (Dunn's white gum) are hardwood species grown in subtropical parts of Australia. *Pinus elliottii* (slash pine), *Pinus caribaea* (caribbean pine) and the hybrid between these two species are grown instead of *P. radiata* in subtropical regions, such as south east Queensland. Table 8.1 shows the most recent regional data for the six main forestry centres. These account for about 80% of the total plantation area. Numbers in brackets indicate the regions shown in Figure 8.2.

Table 8.1: Total plantation areas – Major regions (2005).

Region	Hardwoods	Softwoods	Total
1) Western Australia	270,813	104,480	375,293
4) Green Triangle	130,145	166,650	296,795
6) South East Queensland	31,675	161,052	192,727
11) Murray Valley	6,380	178,100	184,480
13) Central Gippsland	33,298	58,803	92,101
15) Tasmania	155,500	71,600	227,100
Other regions			370,954
Total (2005)			1,739,450

Data from National Forest Inventory (2006).

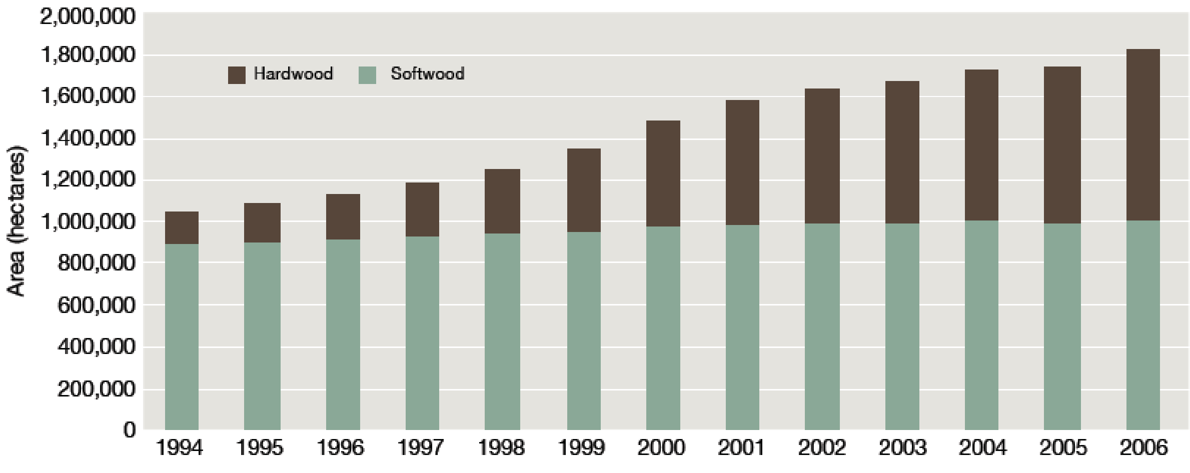


Figure 8.1: Total Plantation Area, 1994-2006 (from National Plantation Inventory 2007b).

Figure 8.2: National Plantation Inventory Regions (From National Plantation Inventory 2006).

The following comments on the six major regions are based mainly on a report by the National Plantations Inventory (2006). Plantations in Western Australia are largely located in the south west of the State (see Figure 8.2). The total plantation area increased from about 131,100 hectares in 1994, as recorded by the first National Plantation Inventory, to over 375,000 hectares in 2005. The vast majority of this increase has been in *E. globulus* plantations, but the rate of expansion is slowing as areas established in the 1990s become available for harvesting and replanting. The area of *P. radiata* is fairly stable at about 60,000 hectares, while the area of *Pinus pinaster* (maritime pine) plantings for salinity control is gradually increasing from the current level of about 44,000 hectares.

The Green Triangle region includes south east South Australia and south west Victoria. This has been a major softwood plantation region since the early 20th century. The region includes some of Australia's most productive *P. radiata* plantations and virtually all the softwood plantations are of this species. *E. globulus* plantation development began on a large scale in the 1990s, and the area planted has nearly doubled since 2000. Virtually all the hardwood plantations in the Green Triangle are *E. globulus*.

The South East Queensland region is mainly based around softwood species, increasingly the *P. elliottii* x *P. caribaea* hybrid. Other significant species include *Araucaria cunninghamii* (hoop pine), a native softwood species, which is grown on about 43,000 hectares of plantations. Hardwood planting has increased significantly in recent years with nearly 24,000 hectares planted in 2001-2005. This includes species such as *E. dunnii* (Dunn's white gum), *E. grandis* (flooded gum) and *Corymbia* species (spotted gums). The Murray Valley region stretches from Gundagai south east towards Melbourne. The total plantation area of 184,480 hectares is 97% softwood, with *P. radiata* comprising about 98% of the softwoods. The Central Gippsland region stretches from Melbourne east to Bairnsdale and north to the Great Dividing Range. About 36% of the area is planted with hardwoods and 64% with softwoods. Nearly 38% of the hardwoods are *E. globulus*, around 31% *Eucalyptus regnans* (mountain ash) and 17% *Eucalyptus nitens* (shining gum). The softwood plantations are virtually all *P. radiata*. Plantations in Tasmania are concentrated across the north of the State and in the south east corner inland from Hobart. The plantations are comprised of about 32% softwoods (nearly all *P. radiata*) and 68% hardwoods (nearly all *E. globulus* and *E. nitens*).

New farm forestry plantations are currently predominantly of eucalypts, such as *E. globulus*, although pines, particularly *P. radiata* are also important (National Forest Inventory 2006). However, there is increasing interest in evaluating the potential of lesser-known species, such as *Eucalyptus cladocalyx* (sugar gum) and *Eucalyptus occidentalis* (swamp yate), that are suitable for low-medium (<700 mm) rainfall environments (Consortium 2001). Oil mallee species, such as *Eucalyptus polybractea*, are also being increasingly planted in low-medium rainfall areas, usually in belts between agricultural crops rather than as block plantings.

Climate Change Impacts

Several studies have previously examined possible impacts of climate change on Australia's forests (e.g., Booth and McMurtrie 1988; Howden and Gorman 1999). It is generally recognised that in Australia's dry environment, water limitations, and the possibility of increasing water shortages, are the greatest concern for plantations in the future (Pittock *et al.* 2001). Tree deaths, especially of *Eucalyptus globulus*, have already been a concern for some plantations, and series of years with well below-average rainfall may lead to tree mortality unless trees have access to sufficient water reserves deep within the profile (Smettem *et al.* 1999). Any reduction in rainfall, as seen in various climate change scenarios, coupled with increased water requirements in a warmer climate (Kirschbaum 2000), is likely to lead to increased tree mortality and represents a major concern for plantation managers in Australia.

Most previous studies have recognised the importance of assessing the effects of atmospheric as well as climatic change. Atmospheric CO_2 is a basic substrate for photosynthesis, which underlies plant growth. Steffen and Canadell (2005) prepared a useful introduction to carbon dioxide fertilisation. Increasing CO_2 concentration can affect tree growth directly through increased photosynthetic rates and indirectly through improved water-use efficiency. It is well established that short-term photosynthetic rates in C_3 plants increase by 25-75% for a doubling of CO_2 concentration (Kimball, 1983; Eamus and Jarvis, 1989; Luxmoore *et al.*, 1993; Drake *et al.* 1997). It is also recognised that the sensitivity of C_3 photosynthesis to CO_2 concentration increases with increasing temperature (Kirschbaum, 1994), and hence the stimulation of plant growth by increasing CO_2 concentration is likely to be larger at higher temperatures (Rawson, 1992), with little stimulation and sometimes even inhibition at low temperatures (Kimball, 1983). Limited observational evidence from international research suggests that the effects of elevated CO_2 decrease as trees age (Steffen and Canadell 2005).

One of the key questions for future water use from plant canopies is the response of stomata to increasing CO_2 concentration. Morison (1985) and Allen (1990) compiled a range of observations from the literature, and showed that stomatal conductance was reduced by about 40% when CO_2 concentration was doubled. Drake *et al.* (1997), however, found stomatal closure by only 20%, and Medlyn *et al.* (2001) found a 21% decrease in stomatal conductance in studies on European trees, and Curtis and Wang (1998) found even lesser stomatal closure in their wider review of studies on woody plants. Reduced stomatal conductance has also been deduced from analysis of herbarium specimens that has shown that the number of stomata on leaves has decreased with historical increases in global CO_2 concentration (Woodward, 1987; Rundgren and Björck, 2003; Kouwenberg *et al*., 2003).

The carbon isotope discrimination between $^{13}CO_2$ and $^{12}CO_2$ can also be used to infer changes in the intercellular CO_2 concentration (Farquhar *et al*. 1982; Korol *et al*. 1999) during historical changes in atmospheric CO_2 (Dawson *et al*. 2002) Using this approach, Arneth *et al*. (2002) and Duquesnay *et al*. (1998) reported data showing some stomatal closure in response to increasing atmospheric CO_2, but Marshall and Monserud (1996) and Monserud and Marshall (2001) found no evidence of stomatal closure in their data sets.

These existing observations and reviews thus still lead to conflicting conclusions, yet this is an area of key importance for understanding the future response of ecosystems to climatic changes. Hence, there is an important need to further review the existing observations and find the commonalities in observations and obtain a generalised global understanding.

In addition, these studies all report on the relative response of plants to climate change when they are either unstressed or only mildly stressed, yet it is of particular importance to understand how plants will respond to episodes of stress. Episodic periods of drought could become more severe through higher temperatures. Under those conditions, plants are likely to close their stomata to conserve water. Nonetheless, water shortages may intensify further under intense atmospheric evaporative demand. It is not known whether elevated CO_2 can confer some kind of protection under these extreme conditions, or whether trees instead become more vulnerable owing to possibly greater leaf area development. This tree response is critically important, but extremely difficult to investigate, and there is very little research information available on it.

Increased photosynthetic rate and decreased water requirement translate into increased tree seedling growth (Luxmoore *et al*., 1993) which has more recently also been observed for mature trees in 'free air CO_2 enrichment' (FACE) experiments in largely undisturbed forests (Herrick and Thomas 2001; Gunderson *et al*. 2002). Based on summarising all available evidence, Gielen and Ceulemans (2001) concluded that the growth of poplar trees may be stimulated by about 30% by doubling CO_2 concentration. As water use efficiency can be greatly enhanced by increased CO_2 concentration (Eamus and Jarvis, 1989), relative plant responses to increases in CO_2 should be most pronounced under water-limited conditions (e.g., Gifford, 1979; Allen, 1990). Growth enhancements by CO_2 are also evident under nutrient-limited conditions (e.g., Idso and Idso, 1994) but these tend to be less than under conditions where nutrition is adequate (Drake *et al*. 1997).

Kirschbaum (1999b) used CenW to investigate the likely response of plant growth to climate change under the range of climatic conditions found in Australia. The model was initialised under current climatic and fertility conditions. Temperature, CO_2 concentration and/or precipitation were then changed, and growth was recorded in response to those changed conditions, but with responses constrained by the set of limitations that had been established under steady-state conditions in the current climate. With that modelling approach, the simulated responses to climate change differed greatly across the continent. For example, positive growth responses to increasing temperature were found in wet and nutrient-limited regions because the higher temperature led to increased nitrogen mineralisation, which stimulated enhanced growth. These same regions showed only slight responses to increased CO_2 concentration because increased carbon production led to immobilisation of nitrogen in soil organic matter. It highlighted an important problem in trying to adapt to climatic changes: not only is the nature of climate change not yet adequately known, but plant responses are difficult to predict even where the nature of change is known.

While Kirschbaum (1999b) examined the effects on generic plant growth, Battaglia and Bruce (in prep.) are carrying out a major project assessing the impacts of climate change on particular Australian plantation species for Forest and Wood Products Australia (formerly the Forest and Wood Products Research and Development Corporation). For example, to anticipate the interactive effect of climate change and elevated CO_2, Battaglia and Bruce (*loc. cit.*) have applied the process-based model CABALA (Battaglia *et al.* 2004) to a selection of *P. radiata* plantations. Preliminary results include five sites in Tasmania and four sites in the Green Triangle. Weather sequences for 2030 and 2070 were produced by applying change estimates to 20 unique weather sequences drawn with starting years from 1960 to 1980. Volume changes are the average of 20 simulations representing planting years for current (1960-1980), 2030 (2015 to 2035) and 2070 (2055-2075). All 2030 simulations start with an assumed atmospheric CO_2 concentration of 450ppm and all 2070 simulations start with an assumed atmospheric CO_2 concentration of 650ppm. Atmospheric CO_2 concentrations are assumed to rise 4ppm each year from the date of planting.

There is considerable uncertainty around down-regulation of photosynthesis at sustained elevated CO_2 levels, but there is some evidence that photosynthesis may be down regulated by around 20% at doubled atmospheric CO_2 concentration (after Medlyn *et al.* 2001, Ainsworth and Long, 2005; Buckley, 2008). This led Battaglia and Bruce (*loc. cit.*) when evaluating the effects of elevated CO_2 up to 700ppm to modify the model such that the maximum rate of CO_2 saturated photosynthesis, A* $\mu mol(CO_2)\ m^{-2}\ s^{-1}$ (eq. A.22 in Battaglia *et al*. 2004), is down regulated according to the following equation:

$$A^*=A_b\ (1.2-0.0006.c_a),$$

where A_b is the base level of maximum photosynthetic rate at saturating CO_2 without acclimation and c_a is the atmospheric carbon dioxide concentration ($\mu mol\ mol^{-1}$).

In evaluating the effects of climate change on production the use of scenarios in the way developed here must be approached with caution. The outcomes can be influenced markedly by the climate model selected, the sites chosen and the modelling assumptions made. To overcome these limitations Battaglia and Bruce (*loc. cit.*) are using a range of climate models and down-scaling techniques are including a sensitivity analysis of assumptions of tree physiological responses such as photosynthetic down-regulation.

Preliminary results suggest that production in Tasmania, which is relatively wet and cold, are likely to rise slightly by 2030 with a smaller gain between 2030 and 2070 in areas where rainfall is abundant. In the north and north-east of Tasmania, where a drying of the climate is forecast, these increases may not occur (for example, at St Helens and Deloraine). In the south of Tasmania, the combination of increased temperature and little or positive changes in rainfall may result in markedly increased production. In the Green Triangle, a sharp decline in rainfall is predicted between 2030 and 2070. Preliminary predictions suggest that this may offset any productivity gains arising from elevated carbon dioxide levels. The impact is most marked in the drier northern extent of the Green Triangle pine estate.

In addition to the impacts on production, a drying climate is likely to affect the water balance of these plantations, decreasing the amount of rainfall that contributes to run-off or drainage. Taking the Caroline site in South Australia as an example, although the total stand water use (tree transpiration, crown evaporation and soil evaporation) declines and the proportion of rainfall that is used by the stand remains unchanged, the amount of water that contributes to deep drainage or run-off falls by 10% between 2000 and 2070.

These preliminary results suggest that the impacts of climate change on forest production may be highly site-specific and will depend upon the extent to which temperature changes and rainfall changes decrease the potential productivity gains through elevated atmospheric CO_2.

Interactions between CO_2 concentration and plant physiological functioning not only affect tree productivity, but also sometimes produce some surprising effects on trees. For example, work with seedlings of *Eucalyptus pauciflora* (snow gum) grown in open-topped chambers indicated that those grown under elevated CO_2 levels suffered 10 times as much leaf damage from a frost event than the seedlings grown under ambient conditions (Barker *et al.* 2005).

Whilst atmospheric change may affect both tree productivity and seedling survival rates, climatic factors are important criteria in selecting appropriate species for planting in forestry systems in different regions. Booth and Jovanovic (2005) analysed the climatic requirements of 31 tree species including species currently important for farm forestry, such as *E. globulus* and *P. radiata*, as well as lesser-known species, such as *Eucalyptus argophloia* (Chinchilla white gum) and *Eucalyptus kartoffiana* (Araleun gum), which may have potential for farm forestry. Their climatic requirements were assessed by bioclimatic analysis of their natural distributions and also from analyses of conditions at trial sites outside their natural distributions both in Australia and overseas. These descriptions were used to generate maps indicating climatically suitable areas under current conditions and under two contrasting sets of future scenario conditions for 2030 and 2070.

Figure 8.3 shows a simplified version of the predicted change in suitable growing region for *P. radiata* (Booth and Jovanovic 2005). Booth and McMurtrie (1988) had shown that most *P. radiata* plantations are located in temperate medium-high rainfall areas of Australia defined by a mean annual temperature of 10-18^oC and mean annual rainfall of 600-1800 mm received mainly in winter or uniformly throughout the year (see Figure 8.3a). This includes the Western Australia, Green Triangle, Central Tablelands, Southern Tablelands, Murray Valley, Central Victoria, Central Gippsland, East Gippsland-Bombala and Tasmania regions shown in Figure 8.2. Figures 8.3b and 8.3c show the location of the temperate medium-high rainfall area under a climate change scenario developed by CSIRO Marine and Atmospheric Research for the years 2030 and 2070 (McGregor 2003) . The main features of this scenario are a 0.85^oC rise in temperature by 2030 and a 2.3^oC rise in temperature by 2070, combined with a percentage reduction in precipitation of 3.9% in 2030 and 10.7% in 2070. These are mean values from across the continent, though the actual data used varied spatially. Differences between current conditions and 2030 are relatively slight. There is some reduction in the climatically suitable area in Western Australia and the unsuitable area in Central Victoria becomes larger. The changes become greater in 2070 with further reductions in the suitable areas in Western Australia and western Victoria being most obvious. However, most of the major *P. radiata* plantation areas remain climatically suitable (see, for example, areas 4 and 11 in Figure 8.2).

Pests and diseases provide other potentially complex interactions between climate change and plant responses. Podger *et al.* (1990) investigated climatic factors affecting the distribution of the soil borne fungus *Phytophthora cinnamomi* in Tasmania. Chakraborty *et al.* (1998) published a useful review of potential impacts of climate change on plant diseases including those which affect tree species, such as *P. radiata* and *E. globulus*. Booth *et al.* (2000a, b) described the climatic requirements of pathogens that either are already present in Australia or might pose a potential threat to trees in Australia. The CLIMEX model (Sutherst and Maywald 1985) is being currently used to study the effects of climate change on pests and diseases important for forestry (Kriticos, D. pers. comm.). A study for the Australian Greenhouse Office (AGO) is using CLIMEX to assess the potential effects of climate change on the distribution of a eucalypt pest and disease (*Mnesampela privita*, Autumn gum moth and *Mycosphaerella* spp., crinkle leaf disease) as well as a pine pest and disease (*Essigella californica*, pine aphid and *Dothistroma septospora*, Dothistroma needle blight). For example, the model predicts that, by 2070, the distribution of *Mycosphaerella* spp. leaf disease will shift south and increase in altitude. The predicted distribution of the disease is being compared with the current and likely future distribution of *E. globulus* plantations in order to examine any potential risks (Pinkard, L., pers. comm.).

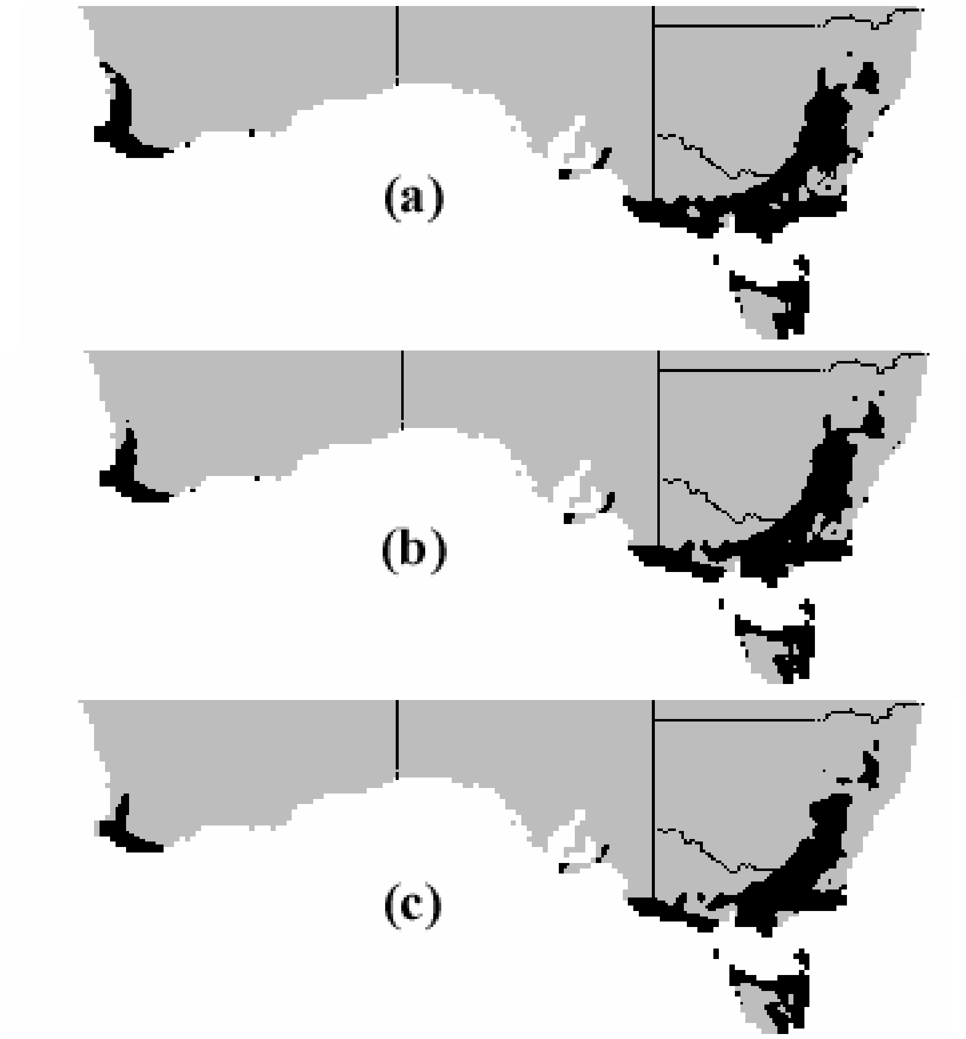


Figure 8.3: Black shaded areas are temperate medium-high rainfall areas suitable for growing *P. radiata* under (a) current climatic conditions, (b) a 2030 CSIRO climate change scenario and (c) a 2070 CSIRO climate change scenario. Prepared using program developed by Booth and Jovanovic (2005) using scenario described by McGregor (2003).

A range of major experiments are either under way or have been proposed to address a number of specific questions about atmospheric change. The Hawkesbury eucalypt experiment is examining effects of increased carbon dioxide using whole-tree chambers. While the enclosures allow CO_2 levels to be increased, it is difficult to reproduce the conditions that are experienced by trees growing in the open. The concern therefore remains whether observed responses to CO_2 would also be found under more natural conditions. Hence, there has been growing interest to conduct FACE experiments where the atmospheric CO_2 concentration is raised around a group of plants without enclosing plants in chambers. Raison *et al.* (2007) reviewed the feasibility of FACE experiments in Australia. Indicative annual running costs are approximately $2M to $4.5M per year for each experiment. They recommend that an initial FACE study should be established either in open dry sclerophyll forest or woodland that typically has a nitrogen fixing understorey. A FACE study could be established in a plantation at a later time with the support of appropriate stakeholders.

Adaptation Options

Current Options for Dealing with Climate Variability

Managing for climatic variability is particularly important for forestry as it can take many years for trees to produce a commercial product. For example, *E. globulus* requires about 12 years to produce a pulpwood crop, *P. radiata* typically takes about 30 years to produce a final sawlog crop and *Acacia melanoxylon* (blackwood) may take 50 or more years to produce high-value timber. The full value of the trees is only realised if the stands complete their full rotation period. Managing for rainfall variability is likely to become more important for forestry as new plantations are increasingly being located in lower rainfall zones to meet natural resource management aims such as salinity control and carbon sequestration (Consortium 2001). For example, Neumann *et al*. (2006) describe how the FloraSearch project is evaluating forestry and agroforestry systems suitable for the 250-650 mm rainfall zone of southern Australia.

Severe droughts have already caused tree deaths in some areas of *P. radiata* and *E. globulus* plantations. For example, in south-eastern New South Wales, *P. radiata* plantations suffered losses as a result of a run of months with below average rainfall starting in April 1997. Rainfall at Albury was less than half the average amount from April to July 1997 (inclusive), and the total for the 12 months to July 1998 was only 417 mm compared to the mean annual rainfall of 706 mm. The dry months coincided with a period of negative Southern Oscillation Index values that started in March 1997 and continued to April 1998 (inclusive). The greatest number of tree deaths occurred where planting densities were high, where soils were shallow and where pine aphids had caused further tree damage (H. Dunchue, State Forests of New South Wales, pers. comm.).

Increasingly, growers can anticipate drought problems and adapt their actions accordingly. Tools such as the Queensland Department of Primary Industries RainMan (www.dpi.qld.gov.au/rainman/), Bureau of Meteorology products on the SILO website (www.nrw.qld.gov.au/silo/), Queensland Department of Natural Resources products on the LongPaddock website (www.longpaddock.qld.gov.au/) and the Bureau of Rural Sciences Rainfall Reliability Wizard (www.brs.gov.au/rainfall/) can assist these analyses. Information on likely El Niño conditions, particularly the Southern Oscillation Index (SOI), is also now available to assist decision-making. Another adaptation to reduced rainfall is the selection of species that are drought tolerant. The Australian Low Rainfall Tree Improvement Group (ALRTIG) is a cooperative involving CSIRO, the Australian National University and organisations from New South Wales, South Australia, Tasmania and Victoria, that is developing improved germplasm for low rainfall (400-600mm) environments.

Adaptation Options for Dealing with Climate Change

A number of policy options are listed in Table 8.2, but these may be somewhat similar across all agricultural sectors and so are not discussed here. Generally there are three situations that forest managers may encounter:

1) *After significant climatic changes have occurred and before establishing a new plantation.* This is the situation that growers may encounter in future decades. In this case the adaptation response for tree growers is relatively simple. They can use the experience gained previously in those places that have a climate similar to that to which the local climate has changed and change species or management options.

2) *The climate changes after plantations have been established.* This is the case when trees have been planted some time ago, but where the rotation length is such that it will take some more years before it is time to harvest the stand, and the climate has changed adversely. In that case, the adaptation options are limited and limited to thinning the stand, adding or withholding fertiliser, or adding water, although irrigation is seldom a practical option.

3) *Significant climatic change has not yet occurred, but it is recognised that conditions may change in the future.* Under those circumstances, different species or provenances may be selected for planting, or trees could be planted at wider spacing from the beginning. These available response strategies could also be described in more general terms, such as by adopting a generally more conservative strategy – to plant fewer trees, select slower-growing, but more resistant ones, or to use less fertiliser. In some already very marginal environments, tree growers may even consider growing no trees at all because of that uncertain future.

The following sections explore some of the individual adaptation strategies that are needed in the above cases.

Genotypes

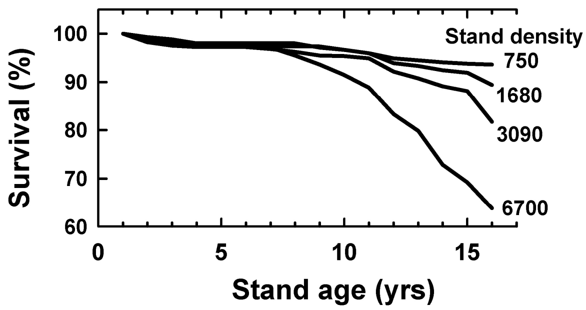
Even though species selection is still important, the choice of material to plant increasingly involves the selection of appropriate provenances (i.e. seed of a species from a particular location), hybrids or clones. In future, the use of genetically modified (GM) material may also be considered, though GM material based on native species would need to be sterile to avoid transfer of genes to native stands. The quality of information available on the uses and environmental requirements of particular trees is rapidly improving. For example, CAB International (2005) has developed a CD-based Forestry Compendium that allows users to select species on the basis of information on distribution, uses, environment and silviculture. The Compendium uses the same descriptions of climatic requirements used in climatic mapping programs (see, for example, Booth and Jovanovic 2005). Generally, the cost of material for planting is a small fraction of plantation establishment costs. Clonal material is most expensive, followed by hybrids, provenances and finally species material of unspecified origin. Selecting the most appropriate species to plant is obviously vitally important, as genetic material cannot be changed once trees are in the ground. The cycle from planting to final harvest is usually at least ten years. The selection of genetic material at planting time therefore has a strong and long-term effect on the stand’s potential biological performance.

In most cases, pulp plantations will probably be able to complete their current rotation before they are significantly impacted by climate change, and different genetic material could be chosen for the next rotation if that seems warranted. That is more difficult for longer-term sawlog plantations that may well grow for long enough to experience a considerable extent of climate change over a single rotation. In this case, it becomes important to choose appropriate genetic material that can grow not only under current conditions but also under the possibly changed conditions in 30 or 40 years time. Selecting the best genotype could then make the difference between profit and loss. More information on the relative performance of particular genotypes in different environments is needed to assist growers to make appropriate choices for both current and future conditions. Even though species change may seem like a relatively easy adaptation option, it is important to also consider the final product, which may limit the full scope for adaptation. Processing facilities usually have specific product requirements, and trees must be chosen to meet these needs.

Spacing and thinning

Simple adaptations to reduced rainfall include planting trees at wider spacings (Smettem *et al*. 1999), as well as thinning existing stands. Wider spacing of trees reduces the competition between trees, and allows each individual tree to exploit a larger volume of soil. This is particularly effective as a safeguard against drought-induced mortality (see Figure 8.4). However, spacing at wider than optimal density may reduce stand growth as trees only partly utilise available site resources. Battaglia *et al*. (2004) have described how computer modelling of tree growth and drought risk can be used to recommend appropriate spacing levels for different environments. Establishment costs per unit of land are not greatly reduced by using lower planting densities, as a similar area of land has to be prepared, and savings in planting stock are likely to be minor. A low planting density may also cause problems with the form of the trees, as wide spaced trees tend to produce many large branches. Hence, while wider spacing is one of the few available adaptation options to guard against drought-induced deaths, it does reduce stand productivity and the overall economic viability of projects under current climatic conditions.

Figure 8.4: The effect of initial planting density (stems per ha) on survival of trees in a loblolly pine plantation (redrawn from Sharma *et al.* 2002).



Watering

Trees are sometimes watered just after planting to assist in the early establishment phase. Under drought conditions, however, farm animals or crops are usually given a much higher priority than forestry plantations. Only small areas of irrigated forestry plantations have been established, as it is not generally possible to justify the cost of irrigating trees. There may be some potential for the wider use of effluent irrigation (Myers et al. 1999), which is seen as a promising means of disposing of effluent and creating some useful product at the same time. In contrast, extensive use of freshwater irrigation for trees seems a very unlikely option, as water will probably become even more expensive in the future and there are likely to be more profitable uses for any available water.

Nutrients

The rate of water loss from plantations is strongly related to the total leaf area of trees. Total stand leaf area can be modified through tree spacing as discussed above, or, more subtly, through adjusting fertility levels. Nutrient-limited stands produce fewer leaves, and that makes them less vulnerable to developing water stress. Reducing leaf area, and hence water loss, through reduced fertiliser application is a possible adaptation option to drier conditions. However, opportunities for adjusting nutrition in forestry systems are limited. Later-age fertilisation is not generally used in forestry plantations and good nutrition at planting is important to ensure successful early growth. Plantations are now almost always established on cleared agricultural land that already has high fertility levels due to many years of fertiliser additions. While lower fertility makes stands less prone to water stress, it also reduces growth under conditions when water is not limiting, and it creates another instance of a conflict between the need to be guarded against adverse conditions in the long term and maximising growth and economic returns in the short term.

Site selection

In regions where climate change is likely to bring reduced rainfall, an obvious adaptation might be to restrict the planting of trees to wetter environments. However, as mentioned in the introduction, forestry is currently tending to move into lower rainfall regions because of the greater availability of cheap land and associated environmental benefits of planting trees in drier, and more marginal, agricultural areas (Consortium 2001). Greatly increased plantings in high rainfall (>800 mm mean annual rainfall) environments may also become restricted in future because of concerns about their impact in reducing catchment runoff (Nambiar and Brown 2001, Keenan et al. 2006).

At the landscape scale, the location of forestry plantings that are directed towards addressing dryland salinity problems will increasingly be driven by improved knowledge of sub-surface groundwater reserves and water flows. A possible adaptation to future drier conditions might be to locate trees in areas where they can make use of groundwater. While this might be a low-cost adaptation option in the short term and have some desirable environmental side-effects, trees may overly reduce groundwater tables to make that option not sustainable in the long term.

Fire management

Any form of forestry is a long-term investment which makes it particularly vulnerable to loss by bushfires. Changed climatic conditions, particularly warmer, drier and potentially windier periods are of concern. The small-scale and relatively isolated nature of most farm forestry plantings provides some protection as it makes it hard for fires to spread from one isolated stand to another, while larger scale commercial plantings can maintain good access networks and staff well trained in fire fighting. Adaptation options if fire risks increased would include allowing greater width in firebreaks and carrying out more frequent controlled burns where appropriate to reduce the risk of wildfires.

Pest and disease management

As information on the likely impacts of climate change on pests and diseases becomes increasingly available this information will assist forest management including the selection of appropriate trees for planting at particular sites, as well as on-going site management.

Weed management

If weeds are present in plantations, they can compete with trees for access to soil resources, especially water. If wider tree spacing is used as an adaptation to lower rainfall, it will allow more light to penetrate stands and the trees will provide less competition for water and nutrients. This could lead to a greater proliferation of weeds and partly negate the benefits of wider spacings. Good weed management is particularly important to ensure good early tree growth and its importance is well recognised in commercial plantations. The quality of weed control is more variable in farm forestry plantings. But as farm forestry becomes more common and practices improve, good weed control should be carried out on all sites anyway regardless of concerns about climate change.

Establishment strategies

Mortality during establishment is a significant risk, particularly for plantings in lower rainfall regions. There is a wide range of establishment strategies available, including tubestock, direct seeding, assisted and natural regeneration, in combination with different site preparation and management regimes. In principle, matching combinations of these to seasonal climate forecasting may provide useful ways of managing climatic risks while minimising financial risks. However, specific research on these as suitable options has not yet been undertaken. In particularly dry countries, such as Israel, tree plantings sometimes include special site preparation, which increases the micro-catchment area of individual trees or small stands (e.g. Lövenstein et al. 1991). Strategies such as these could be used in response to drier conditions, but are generally too expensive for current use.

Climatic risks

Tree selection is usually based on matching known tree characteristics to long-term mean climatic data, but changing climates will require the suitability of particular trees to be reassessed for specific locations. When carrying out these analyses it would be prudent to place increasing reliance on more recent climatic records. For example, it may be advisable to consider frost risks on the basis of data from the last twenty-five years rather than the last hundred years, or to fit a linear trend of frost incidence over the past record to provide the best guidance to likely conditions in the future.

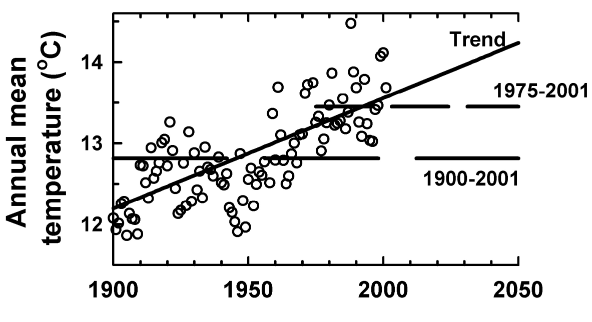


Figure 8.5: Mean annual temperature from 1900 to 2001 for Low Head, Tasmania. This data set is chosen as an example for a site for which a long climate record is available. The solid line gives a linear fit to the data. The long-dashed lines gives the mean of all data from 1900 to 2001, and the shorter-dashes give the mean temperature from 1975 to 2001.

Risks of Maladaptation

Many forest managers would like to be more conservative in their management to be prepared for climatic changes, but the imperative to achieve maximum growth rates and maximum economic returns makes such a cautious strategy difficult to implement. A typical example is seen in the rapid expansion of *E. globulus* plantations which has led them to be pushed to, and perhaps sometimes beyond, reasonable rainfall limits as cheaper land has been sought for further expansion of the plantation estate. These economic imperatives make it difficult to cope even with current climatic variability, let alone allow the extra flexibility of dealing with future climate change.

The worst case scenario for a tree species under climate change would be death due to its present environment becoming totally climatically unsuitable. This may constitute a real risk for some native species with very limited climatic ranges growing in natural ecosystems (Hughes *et al*. 1996), although many species may be more adaptable than their natural distribution suggests (Kirschbaum 2000; Booth 2007). However, Figure 8.3 and the analyses of Booth and Jovanovic (2005) suggest that commercial species are not generally in immediate danger of their most commercially important locations becoming climatically unsuitable. This is probably because commercial species tend to be planted in relatively good climatic locations for growth and these major plantation areas tend to be somewhat different to their absolute limits to growth. For example, most *P. radiata* plantations are in locations with mean annual temperature below 14^{o}C, though some areas are in locations above 16^{o}C Booth and McMurtrie 1988). Mean annual temperatures would probably need to rise by well over 2^{o}C before they made the major commercially important regions totally unsuitable for species such as *P. radiata* and *E. globulus*. However, changing climatic conditions may affect pest, disease and fire risk conditions at particular sites and reduce growth rates long before it becomes completely climatically unsuitable for a particular tree species.

More extreme adverse climatic changes may even cause the death of some trees. Recent drought conditions have already caused significant tree losses in some areas. Though it is not yet possible to be certain that recent droughts in southern Australia are part of climate change, it appears increasingly likely that they are.

Costs and Benefits

The Allen Consulting Group prepared a report for the Australian Greenhouse Office (AGO 2005) that discussed possible costs and benefits of climate change for several agricultural sectors and forestry. Though it did not provide a quantitative analysis it suggested a framework for this type of analysis and identified some of the key issues that would need to be considered. The current annual value of the wood and wood products industries is about $18 billion, and it employs about 83 000 people (BRS 2007). Vulnerability is a function of the exposure to climate factors, of the sensitivity to change and of the capacity to respond and adapt to that change. Forestry has significant exposure to climate change in terms of reduced rainfall, drought, increased fire hazard, pest infestations and soil erosion. Immature forests are particularly susceptible to drought. Sensitivity of the plantation industry reflects the responsiveness of the system to climatic influences, and the degree to which changes in climate might affect it in its current form. Sensitive systems are highly responsive to climate and can be significantly affected by small climate changes. The AGO (2005) report assessed forestry to be moderately sensitive. Though the two major plantation species have broad climatic ranges, many native species have narrow climatic ranges. Forestry was considered to have a high adaptive capacity as alternative species could be planted if required, but long planning horizons could make changes difficult. The report concluded that forestry has the potential to benefit from early attention to adaptation planning through better selection of species and management planning that takes climate change into account.

While climate change creates some potential problems for forest managers, it also provides new opportunities. There is increasing interest in biosequestration i.e. planting trees to remove carbon dioxide from the atmosphere and store the carbon in growing trees or wood products. Australia is largely on track to meet its Kyoto Protocol commitments almost entirely thanks to trees, in particular the reduced clearing of woodlands for agriculture and increasing the areas of plantations (AGO 2006). The Prime Ministerial Task Group on Emissions Trading (2007) advised that "undertaking low-cost measures to reduce deforestation and promote carbon sinks, both within Australia and internationally, should be an immediate priority". For example, in November 2007 Woodside announced that it has entered into a $100 million program with CO2 Australia Ltd to plant mallee trees to help offset carbon emissions from the Pluto gas field in Western Australia's north west. The Australian Bureau of Agricultural Research Economics (ABARE) has examined climate change issues for agriculture and forestry (Gunasekara *et al*. 2007), including a consideration of costs and benefits of forest-based carbon offsets.

There is also potential for forest products and residues to be used for the production of bioenergy. Raison (2006) estimated that about 14-16 million cubic metres a year of forest waste products are available that could be used for energy generation by co-firing, bioenergy plants or small scale gasification. There is also increasing interest in the production of cellulosic ethanol as a biofuel from forest products or residues, as these can often be produced on lower-value land than agricultural alternatives.

Knowledge Gaps and Priorities

Effective adaptive responses rely on good knowledge of anticipated changes. Therefore, a high priority for research must be the generation of more reliable projections of likely climatic changes at the regional level. However, it must be acknowledged that there will always remain fundamental uncertainty in climate change predictions due to uncertainty in emissions scenarios. That is not an uncertainty that can be reduced through further scientific work. Future emissions will largely depend on technical, political, social and economic factors and are thus inherently difficult to predict. Furthermore, the global society is actively working to modify future emissions through processes such as the Kyoto Protocol. Actual future emissions and consequential climatic changes will thus depend in part on the success or failure of these international attempts at emission control.

Priority research areas for forestry adaptation to climate change include:

1) Bioclimatic analyses to improve knowledge of the climatic requirements of particular genotypes and to identify particularly vulnerable plantation sites for monitoring;

2) Evaluation of the impacts of high CO_2, and drought risk on tree mortality, including identification of the optimal strategy between high growth (e.g. dense stands with high leaf area) and risk aversion (e.g. sparse stands with low leaf area) for particular sites and particular trees/products.

3) More detailed assessment of drought tolerance of important species and development of more drought-tolerant genotypes;

4) Enhancement and application of process-based growth models using information from the other priority studies and extending findings from individual sites to large areas, including cost/benefit studies of alternative adaptation strategies;

5) Development of improved assessments of pest, disease and weed risks; and

6) Development of improved assessments of bushfire risks.

Table 8.2: Summary of climate change adaptation options for the forestry industry indicating whether the option 1) has already been assessed or is a remaining knowledge gap, 2) is highly feasible, 3) would be feasible / effective immediately, or 4) should be a high priority for research, assessment and implementation in developing adaptation strategies.

Adaptation options	Options already assessed	Options with high feasibility	Immediacy	Priority activities
Policy level				
Maintain forestry R&D capacity, undertake further adaptation studies which include costs/benefits and streamline rapid R&D responses	✓	✓	✓	✓
Develop further bioclimatic analysis and forest systems modelling capabilities and quantitative approaches to risk management	✓	✓	✓	✓
Ensure communication of broader climate change information	✓	✓	✓	✓
Provide training to improve self-reliance and to provide knowledge base for adapting	X	✓	✓	✓
Encourage public sector support for a vigorous forest research and breeding effort e.g. Australian Low Rainfall Tree improvement Group (ALRTIG)	✓	✓	✓	✓
Encourage financial institutions to be responsive to changing industry needs	X	✓	X	X
Support continuing commitment from all levels of government for pest, disease and weed control including border protection	✓	✓	✓	✓
Promote introduction of climate change adaptation into forest management systems	X	?	X	X
Forest management				
Develop systems to assist genotype selection that takes into account likely climate changes over the whole rotation.	X	X	✓	✓
Provide advice on appropriate spacings for different genotypes and environments.	✓	✓	✓	✓
Improve knowledge of water use of plantations under climate change.	X	✓	✓	✓

Adaptation options	Options already assessed	Options with high feasibility	Immediacy	Priority activities
Provide advice on opportunities to use nutritional adjustments as an adaptation to climate change.	X	X	X	X
Develop systems to minimise fire risk e.g. by assisting in design of firebreaks and planning of controlled burns.	X	✓	✓	✓
Provide advice on appropriate weed management strategies for particular plantation systems.	X	✓	✓	✓
Improve pest and disease predictive tools	✓	✓	✓	✓
Improve monitoring and responses to emerging pest, disease and weed issues	✓	✓	✓	✓
Provide improved advice on establishment techniques to minimise tree deaths	✓	✓	✓	✓
Improve use of climatic data in species-site selection e.g. give greater weight to more recent climatic data	X	✓	✓	✓
Develop participatory research approaches to assist pro-active forest management decision making	✓	✓	✓	✓
Expand routine record keeping of weather, production, degradation, pest and diseases, weed invasion	X	✓	✓	✓
Provide tools and extension to enable foresters to access climate data and interpret the data in relation to their permanent sample plot (PSP) records and analyse alternative management options	X	✓	✓	X
Climate information and use				
Improve regional level climate change modelling to provide more reliable scenarios to assist decision making in forestry	✓	X	✓	✓

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9: BROAD ACRE GRAZING

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Key Messages:

- The main challenges facing the grazing industry are likely to be declines in pasture productivity, reduced forage quality, livestock heat stress, greater problems with some pests and weeds, more frequent droughts, more intense rainfall events, and greater risks of soil erosion.
- Increased adoption of climate forecasting to inform existing strategies for coping with climate variability will assist the grazing industry in dealing with the early stages of climate change (but these strategies need to incorporate considerations of long-term climate change trends).
- The adaptation challenge needs to be clearly defined by quantifying the range of impacts uncertain climate change will have on the grazing industry and framing these challenges in terms of existing management pressures. Likely responses of pastoralists and policy makers to these impacts need to be determined and comprehensively evaluated.
- The most arid and least productive rangelands may (low confidence) be the most severely impacted by climate change, while the more productive eastern and northern rangelands may provide some opportunities for slight increases in production. However, a rigorous analysis of the regional variation in impacts of climate change on rangelands still needs to be conducted.
- Participatory research approaches that utilise producer knowledge will assist in assessing vulnerability of the pastoral industry to climate change, indentifying practical adaption options, and determining the limits of adaptations for coping with climate change.

Introduction

Extensive grazing is by far the most widespread agricultural land use in Australia. Most of the country is unsuitable for intensive agricultural production and is used instead for low intensity production of beef and sheep (meat and wool).

The grazing industry has been an important contributor to the overall economic growth of Australia. The impact of historical climate events on beef, wool and sheep meat industries has been the subject of a large number of studies ranging in scale from on-farm to continental scale (Campbell 1958; Gibbs and Maher 1967; Anderson 1979; Anderson 1991) The sensitivity of agricultural production to climatic fluctuations has been identified as an important contributor to volatility in Australia's economy (White 2000). For example, modelling studies by ABARE determined that the drought event of 1994 to 1995 reduced the gross value of farm production by as much as 9.6% or $2.4 billion (Hogan *et al.* 1995; Hogan *et al.* 1995).

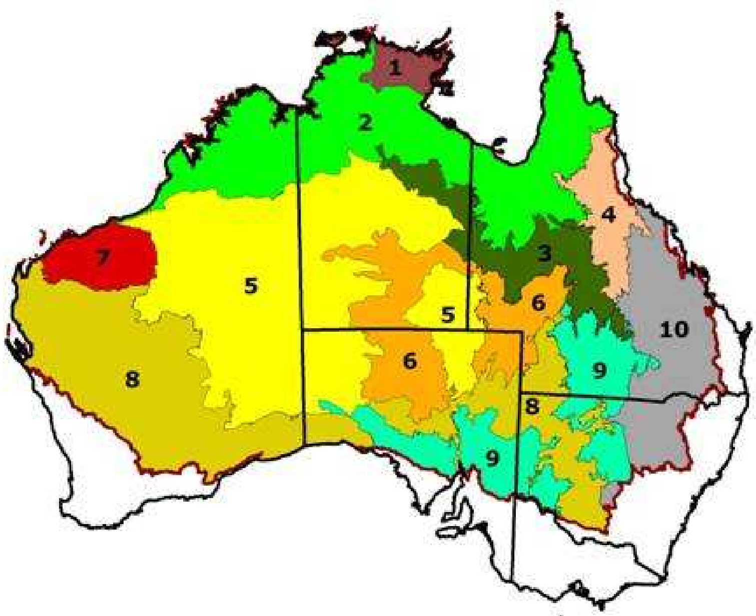
The native and improved pastures that form the rangelands cover over three quarters of the continent (Figure 9.1). The diversity of Australia's rangelands reflects their broad geographic extent across the country. The rangelands have been classified into ten categories based on grouping Interim Biogeographical Regions of Australia with similar climatic characteristics (Figure 9.1). These range from the central deserts, to southern temperate sheep grazing areas, to the highly-modified productive eastern subtropical woodlands, to the northern tropical savannas.

For the purposes of this chapter we simplify the classification of rangelands into just three categories: 1) the arid deserts of the centre, 2) the adjacent semi-arid region, which includes grasslands, and 3) the remaining more mesic rangelands consisting of the tropical savannas to the north and productive subtropical woodlands to the east (Figure 9.2). The variety of ecological characteristics within the rangelands means that there are likely to be regional and local differences in the effects of climate change.

Climate change will add to and exacerbate existing pastoral management challenges such as undesirable grass species, shrub invasions, soil erosion, salinisation, soil acidification, and problems with animal nutrition and health. While technological advances have been developed to address some of these issues (Quirk 2002), with climate change it will become even more important to ensure widespread adoption of these practices.

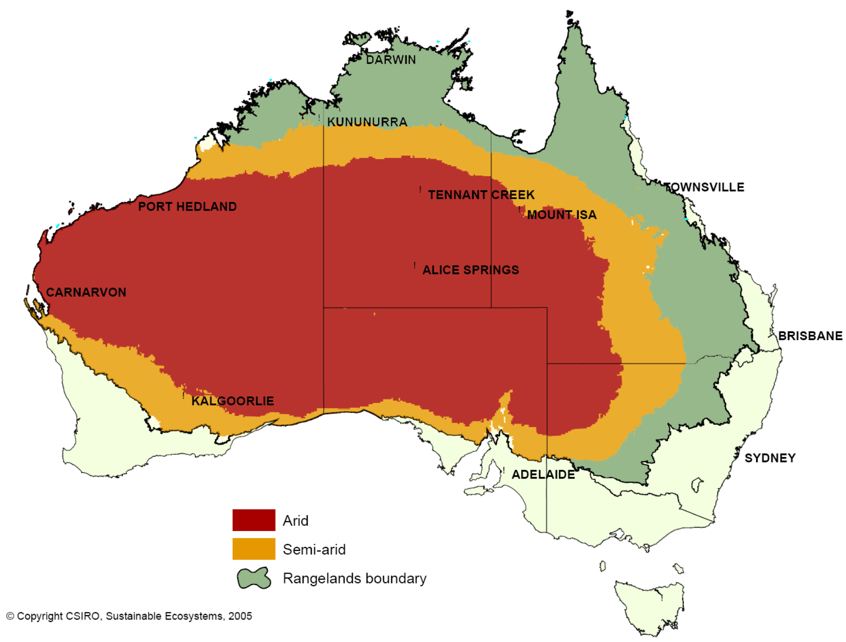
We review the potential impacts of climate change on Australia's grazing industries and options for adapting to these changes. We also identify a number of key knowledge-gaps that need to be addressed in order to prepare adaptation strategies for the pastoral industry and outline the requirements for a coherent research and delivery framework that would enable the pastoral industry to more effectively consider climate impacts and adaptations in their decision-making.

Figure 9.1: Grazing Land Management Zones: classification of Australian rangelands based on groupings of IBRA regions with similar pastoral characteristics.



1. Arnhemland and Tiwi Islands
2. Tropical savannas
3. Mitchell grass downs
4. Einasleigh and Desert Uplands, north Queensland
5. Arid deserts
6. Central Australia cattle grazing
7. Pilbara
8. Southern Australia sheep and cattle grazing
9. Extensive sheep grazing
10. Highly modified rangelands

Figure 9.2: Classification of Australian rangelands based on a moisture index: Arid (rainfall < 20% of potential evaporation [≈250 mm yr^{-1}]), Semi-arid (rainfall = 20 to 40% of potential evaporation [≈250-350 mm yr^{-1}]), remainder (rainfall > 40% potential evaporation [≈350 mm yr^{-1}]).



Climate Change Impacts

Climate change will impact the pastoral industry through complex interactions involving climate, atmospheric composition, grazing management and a potentially wide range of indirect impacts that may affect animal production. But the most direct influences will be through changes in forage production and livestock performance. In the longer-term, if graziers do not adjust their land management practices to suit the changed climate conditions, then risks of land degradation may increase and/or new opportunities may be lost (McKeon *et al.* 2004).

Animal performance (e.g., live weight gain, wool growth, flock/herd reproduction and mortality, and milk production) is strongly related to the availability of young, digestible plant material (Mannetje 1974; Ash *et al.* 1982; McLennan *et al.* 1988; Howden *et al.* 1999c), which in turn is strongly influenced by the frequency of weather conditions suitable for plant growth. Grazing history (frequency and intensity) and pasture management (burning, tree regrowth control – or legislated lack thereof, applied nutrients, herbicide use) can also have major impacts on the botanical species composition and hence diet quality (McMeniman *et al.* 1986; Orr 1986; Ash *et al.* 1995), as does, the availability of soil nutrients such as nitrogen and phosphorus (McLean *et al.* 1990; O'Rourke *et al.* 1992; McCosker and Winks 1994), extent and duration of beneficial flooding (White 2001) and atmospheric CO_2 concentration (Lilley *et al.* 2001b). Thus any impacts of climate change on the composition and growth of pastures will have important consequences for animal production (McKeon *et al*. 2004).

To ensure that pastoral enterprises remain productive and sustainable, graziers have to tackle several management concerns. These include: (1) pasture productivity, (2) forage quality (3), pests, diseases and weeds, (4) botanical changes pasture composition, (5) soil erosion and (6) animal husbandry and health (Hall *et al.* 1998). We therefore review current understanding of how atmospheric/climate change will affect each of these six components of pastoral management, and follow this with a section presenting some of the management options that could be employed to cope with these impacts.

Pasture productivity

Rising atmospheric CO_2 levels, increasing temperature, and changing rainfall regimes will alter pasture productivity. Pasture growth is expected to be dominated by changes in rainfall (Hall *et al.* 1998; Crimp *et al.* 2002), but changes in the temporal distribution of rainfall may reduce productivity in regionally specific ways, even if annual averages remain the same. This is because the effectiveness of rainfall could be reduced by projected increased variation within seasons (fewer, more intense rainfall events) and from year to year (more droughts and floods). Changes in river flow regimes and beneficial flooding may alter the production of ephemeral pastures on floodplains. Rising temperatures could benefit pastures in cooler, southern climates by increasing the length of the growing season and reducing frost damage. However, increased plant growth in the cooler months could deplete soil moisture at the expense of subsequent pasture growth in the spring. These seasonal changes in forage production and availability could pose additional challenges for grazing management. In warmer climates, increased heat stress, and increased evaporative demand would likely have negative effects on pastures. While rising CO_2 will enhance plant growth (Gifford 1988; Lilley *et al.* 2001a), through improved nitrogen and radiation use efficiencies, plants differ in their responsiveness to CO_2. Species differences will be further enhanced by changing species interactions, such as altered patterns of water and nitrogen use within plant communities.

Beneficial flooding on the vast floodplains of arid and semi-arid Australia makes a significant contribution to ecosystem processes and pastoral productivity. Once water levels recede vast quantities of ephemeral vegetation emerge, and these growth responses differ substantially between those generated by rainfall (Edmondston 2001; White 2001). Furthermore a different suite of species is seen in winter to those seen if rain or floods occur in summer. Each response has differing palatability, nutrition, and persistence. Given this natural variability it is difficult to accurately assess the impacts of climate change, however long-term changes in rainfall, temperature and evaporation may alter flow regime on these river systems causing changes in inundation area, waterhole persistence and connectivity, natural ecosystems and production of herbage (Cobon and Toombs 2007a). The driest and wettest extremes examined showed a range of change in mean annual flow at Windorah of -7 to 2% by 2030, the median and dry scenarios showed a reduced frequency of low daily flows (<1000 ML/d), extended periods of no flow, reduced inundation from small flood events and reduced peak flow, compared to a base period from 1961-1990.

In the past, measurements of leaf physiology have often been used to emphasise the differences in CO_2 responses between plants with the C3 (most woody and herbaceous plants, and cool season grasses) and C4 (tropical grasses) photosynthetic pathways. Rising CO_2 increases water- and nitrogen use efficiency in both C3 and C4 plants but, increases in light use efficiency, mainly due to reduced photorespiration, are largely restricted to C3 plants. However in rangelands, moisture and nitrogen are generally more limiting to plant growth than light, so theoretical leaf level advantages of C3 plants (greater light use efficiency) may be constrained in real-world environments. Indeed, in C3 pastures where the components of response to CO_2 were experimentally separated, increases in plant production were found to be almost entirely attributable to indirect effects of moisture savings, rather than directly stimulated photosynthesis (Volk *et al.* 2000; Niklaus *et al.* 1998). There is growing evidence that the most important influence of CO_2 on water-limited plant communities will be through altered patterns of water use and, correspondingly, C4 pastures may not be substantially less responsive to CO_2 than C3 pastures (Morgan *et al.* 2004; Wullschleger *et al.* 2002; Owensby *et al.* 1993). For example, a statistical meta-analysis of the literature between 1980 and 1997 on non-domesticated grass (*Poacaeae*) species (Wand *et al.* 1999) found that the biomass of C_4 species under doubled CO_2 concentration was 33% above that under ambient CO_2 concentration while that figure was 44% for the C_3 species. It now seems that other physiological and morphological attributes of plants may be more important than photosynthetic pathway in determining differences in species responses to CO_2, particularly in natural, mixed species vegetation.

There are strong interactions of pasture responses to CO_2 with other variables such as temperature, soil moisture and soil nutrient availability, especially nitrogen (Fischer *et al.* 1997; Suter *et al.* 2002). Consequently, when increases in CO_2 occur in field conditions (e.g. in Free Air Carbon-dioxide Enrichment [FACE] experiments) the growth response, while still present in both moist temperate (Campbell *et al.* 1997) and arid (Smith *et al.* 2000) conditions, can be even more variable (Nowak *et al.* 2004). This is especially so after several years when pasture species composition has changed under elevated CO_2 concentration owing to differential increases among species of the number of seeds produced (Edwards *et al.* 2001) and other competitive effects (Smith *et al.* 2000).

Studies on livestock carrying capacity across the rangelands indicate the non-linear response to rainfall (Wilson and Harrington 1984). Small changes in spatial climate are associated with large relative changes in livestock carrying capacity. Pasture modelling studies that have calculated safe livestock carrying capacity from resource attributes and climate data (Scanlan *et al.* 1994; Johnston *et al.* 1996; Day *et al.* 1997) also indicated the sensitivity to small variations in climate. In a detailed study of Queensland native pastures (Hall *et al.* 1998), calculated climate change impacts on 'safe' carrying capacity varied considerably across the State depending on whether moisture, temperature or nutrients were the limiting factors. Without the effect of doubling CO_2, warmer temperatures and ±10% changes in rainfall resulted in –35 to +70% changes in 'safe' carrying capacity depending on location. With the effect of doubling CO_2 included, the changes in 'safe' carrying capacity ranged from –12 to +115% across scenarios and locations. When aggregated to a whole-of-State carrying capacity, the combined effects of warmer temperature, doubling CO_2 and ±10% changes in rainfall resulted in 'safe' carrying capacity changes of +3 to +45% depending on rainfall scenario and location. A major finding of the sensitivity study was the potential importance of doubling CO_2 in mitigating or amplifying the effects of warmer temperatures and changes in rainfall.

Under similar climate change conditions in central Queensland on soils of average fertility without trees, changes in native pasture growth were -14% and 7% for reduced and enhanced rainfall respectively (Cobon *et al.* 2005a), however higher variability of annual growth associated with reduced rainfall scenarios may make livestock management more challenging in future (Cobon and Toombs 2007b).

Forage quality

Three major aspects of forage quality for animal nutrition are energy supply (non-structural carbohydrate), protein (N) content, and digestibility. All of these forage attributes decline with age of the herbage Stimulation of forage production by CO_2 comes at the expense of declines in forage protein content in (Wand *et al.* 1999), and increases in forage non-structural carbohydrates in C_3 species (Wand *et al.* 1999; Lilley *et al.* 2001b) but not C_4 (Wand and Midgley 2004) and decreases digestibility of tropical grasses, although there may be little change in digestibility of other species (Lilley *et al.* 2001b). Warmer conditions tend to significantly decrease non-structural carbohydrate concentrations (and digestibility in tropical species) while also slightly reducing leaf N-content. The combined effect of increases in forage quantity but declining quality depends on the balance between reduced protein intake by the animal and increased metabolisable energy intake which fosters efficient protein utilisation by ruminants (Beever 1993). The impact of elevated CO_2 and temperature on the synchrony between protein and utilisable energy of forage in ruminant nutrition has not been investigated.

A pasture and animal model (GRASP) that used green days as a proxy for forage quality and liveweight gain showed that, when rainfall was not limiting, increased temperatures in central Queensland triggered a response in pasture growth and liveweight gain (LWG/hd) that was associated with a longer growing season during winter (Cobon and Toombs 2007b). However the low rainfall scenarios were associated with higher risk of low annual LWG/hd (10% versus 20% chance of <140 kg/yr) by 2030, and higher variability of annual LWG/hd.

Pests, diseases and weeds

Historically the grazing industry has demonstrated some degree of vulnerability to pests, disease and weed infestation (Mcleod 1995; Sutherst 1990; Sutherst *et al.* 1996) and the following examples serve to illustrate the costs involved. In their review of potential climate change impacts Hall *et al.* (1998) reported that McLeod (1995) estimated that cattle ticks cost the northern tropical beef cattle industry $41 million annually in control measures and $91 million in productivity losses. Roundworms, lice and blowflies cost the Australian sheep industry $552 million annually in control measures and production losses (Mcleod 1995). The cost of weeds to the Australian wool industry was estimated at

10% of the value of the total woolclip (ARMCANZ 1996). Chippendale and Panetta (1994) estimated the cost of parthenium weed to the Queensland cattle industry was $16.5 million annually. Any climate-induced changes in pests and diseases will therefore have significant management and economic implications.

A major risk to the grazing industry from climate change relates to the potential change in the distribution of pests, feral animals, diseases and weeds, particularly a southward range shift of tropical pests following warming conditions. However, in the context of shifting species distributions under climate change, more care will be needed in treating all 'undesirable' pasture species as a problem requiring control. For example, in those rangelands areas where climates become harsher, the most 'desirable' forage plants may start being replaced by hardier plants that are less suitable as forage, but better suited to the changing climate. It will be more productive to recognise, facilitate and direct climate-induced changes in species distributions rather than trying to completely prevent them.

Botanical change in native pastures

In the past, the species composition of native pastures has fluctuated in response to climate variability and changes in grazing pressure (Park *et al.* 2003; McKeon *et al.* 2004). Orr (1986) found that invasion by *Aristida latifolia* occurred during a series of above average summer rainfall years whilst species occurrence declined during drought years. Similarly Bisset (1962) concluded that the invasion of the undesirable *Heteropogon contortus* into the Mitchell grasslands was associated with wetter years in the early 1950's. Thus, future changes in rainfall (annual average, seasonal distribution, and year-to-year variability) are likely to lead to changes in species composition. Where climates become hotter and drier, pasture composition is likely to shift to more xeric species that may be less suitable for grazing, and grazing management practices may have to change to match the new vegetation and climate. However, offsetting any reduction in rainfall is the increasing water use efficiency under the increasing CO_2 concentration.

Further changes in rangeland vegetation are expected in response to rising atmospheric CO_2 concentration (Warwick *et al.* 1998; Howden *et al.* 1999b; Howden *et al.* 2001b). Rising CO_2 will affect pastures by changing the temporal and spatial patterns of soil moisture availability: higher levels of CO_2 delay soil moisture depletion following rainfall events (Gifford *et al.* 1996) thereby increasing the availability of moisture deeper in the soil profile. Differences in species responses to CO_2 are therefore likely to be strongly influenced by differences in rooting patterns and the ability of plants to rapidly exploit savings in soil moisture from reduced transpiration of other plants. Deep-rooted woody plants and legumes are likely to be advantaged over grasses at higher CO_2 levels, both because of higher CO_2-sensitivity of growth (Ainsworth and Long 2005) and because of the ability to tap deep water while still competing with grasses for moisture in shallow soil layers.

In formulating adaptation responses, it will therefore be important to determine how increases in CO_2 and climate change will interact, and ultimately change the spatial distribution of rangeland plant species.

Soil erosion

The modelling of regional climate change in Australia, which was used to prepare the CSIRO climate change scenarios (CSIRO 2007), projects increasing rainfall intensity on rainy days (mm/day) and more dry days per year over most of Australia (Tebaldi *et al.* 2006). Such changes in patterns of rainfall intensity are likely to increase the risks of soil erosion. This will likely be exacerbated by increased year-to-year variability in rainfall, with more droughts and more floods, and therefore a greater chance of erosion events where a wet year follows a drought. During periods of reduced rainfall, plant cover declines and the rangelands of Australia become highly susceptible to soil erosion. Erosion reduces pasture productivity through loss of valuable soil nutrients (nitrogen and phosphorus) and loss of infiltration capacity. Thus during periods of enhanced soil erosion a small loss of surface soils will remove a large proportion of the available soil nutrients and hence result in markedly reduced potential productivity (McKeon and Hall 2000). In areas where climate models simulate increases in extreme daily rainfall, in conjunction with reductions in annual rainfall amounts and/or increases in interannual rainfall variation, soil erosion may become an increasingly challenging management consideration.

Animal husbandry and health

Animal health, as with the other management issues listed above, is intrinsically linked to the exploitation of animal behaviour or traits that provide some form of adaptation to existing climate conditions. The upward trend in animal numbers in Australia has been made possible by continued breeding improvement in livestock, especially drought resistance in sheep and cattle, resistance to pests and diseases (Lloyd and Burrows 1988). Climate change will substantially increase the frequency of heat stress days, particularly in northern Australia (Howden and Turnpenny 1997; Howden *et al.* 1999a) reducing productivity, decreasing reproductive rates and increasing concerns about animal welfare in locations where grazing populations are concentrated, such as feedlots. As conditions in southern regions become harsher, pastoralists will be able to use hardier northern breeds (and crosses), but this will come at a cost because heat-stress-tolerant breeds tend to be less productive, have lower fecundity and have lower meat quality.

Other impacts

In addition to direct climate change impacts, indirect effects such as changes in fire patterns, local and international markets, land use and economic returns (price vs. costs) are also likely to shape the nation’s future grazing industry. For example, shorter, milder winters in the northern hemisphere (Keeling *et al.* 1996; Myneni *et al.* 1997) may alter global demand for wool. In the case of meat, prices received by graziers are strongly influenced by production of overseas competitors (influenced in turn by world grain production) and hence global variation climate change impacts will also influence the financial performance of local grazing enterprises (White 1972; Herne 1998).

Enterprises operating at the extreme of their natural range maybe forced to change land-use under climate change conditions. For example, dryland cropping is an important industry for the Fitzroy Basin, but it is located at the northern margin of the wheat cropping region of Australia. Prior to the 1970s, the Emerald region was primarily used for grazing beef cattle despite the potential for higher gross margins in cropping. Subsequently in the next 30 years cropping developed in importance and it is possible that the relative suitability of cropping versus grazing is an artefact of recent climate (Howden *et al.* 2001a). If the increase in cropping was due to long-term multi-decadal climate variability then cropping is likely to decline in the region as conditions return to those experienced earlier in the record. If the increase in cropping was related to climate change (a persistent upward or downward trend in climate) then cropping in the region is likely to persist. These changes in land use influence the natural resources and one possible impact is the sediment loads in rivers and their eventual deposition onto the water around the southern part of the Great Barrier Reef. More cropping land-use and less grazing is likely to be associated with higher sediment loads, whereas decreased cropping and more grazing with lower sediment loads, compared to 1961-1990 (Cobon *et al.* 2007).

Regional variation in impacts

The geographic diversity of rangelands (Figures 9.1 and 9.2) combined with regional variation in climate change projections (Figures 1.2 and 1.3) means that responses of rangelands to climate change are likely to differ from region to region. Anticipating this variation and engaging with pastoralists directly will assist in preparing an appropriate range of adaptation strategies for land managers. A comprehensive analysis of regional impacts of climate change, combining current climate projections with ecosystem models, has yet to be conducted. Accepting the caveat that regional projections of climate change involve a high degree of uncertainty and that rigorous quantitative analyses have yet to be conducted, we summarise what some of the possible regional differences in climate change impacts across the rangelands may be.

The direct effects of CO_2 will benefit pastures mainly by increasing the efficiency with which plants use limiting soil moisture resources. This benefit may be greatest in ecosystems receiving intermediate amounts of rainfall (about 500 – 1000 mm yr^{-1}, depending on latitude) (Nowak *et al.* 2004; Stokes and Ash 2006) where water is limiting during most periods of active plant growth. In very arid climates, high rates of evaporation from surface soils may limit the potential for any CO_2-induced water savings to benefit plant growth (although this may depend on how rainfall regimes, soil properties, and rooting patterns influence when and where plants access moisture in soil profiles). The stimulating effects of rising CO_2 on pasture production may therefore be weakest in the central arid rangeland. However, it remains a research question as to the extent that pasture growth in arid rangelands can respond to the increasing atmospheric CO_2. In the more mesic savanna and woodland rangelands, rising CO_2 may stimulate pasture growth in the short term, but this effect may be partly offset if tree biomass increases in the longer term. Tree biomass in rangelands is dependent not only on environmental conditions but also on the ability of producers to control trees, which depends on both economic factors and legislation. Semi-arid grasslands, such as the Mitchell grass downs, may therefore receive the greatest benefit from rising CO_2. However, stimulation of forage production by CO_2 comes at the expense of declines in forage quality. Furthermore, CO_2 will also favour the encroachment of woody weeds into grasslands, so more effort may be required in weed control.

Changes in rainfall and temperature are both projected to have their greatest negative impacts in the arid rangelands (Chapter 1). Rising temperatures are likely to be greatest towards the centre of Western Australia, while drying trends are projected to be greatest across the central to south western parts of the country (Figures 1.2, 1.3 and 9.2). The semiarid mixed sheep and cattle grazing areas in the southwest of the rangelands are also projected to be adversely affected by declining rainfall.

The more productive northern and eastern rangelands are likely to be the least adversely affected by climate change (Crimp *et al.* 2002). The northern savannas are the only area of the country where rainfall is not projected to decline with climate change, and the proximity to the coast should moderate increases in temperature (Chapter 1). However, monsoon rains are projected to increase in intensity, increasing the risks of soil erosion and potentially reducing the effectiveness of rainfall (by increasing runoff and reducing available soil moisture for plant growth). In the eastern woodlands there is projected to be some drying and increases in year-to-year variability in rainfall may increase the frequency of droughts (Cai 2003; Nicholls 2003; Whetton and Suppiah 2003). Moderate amounts of warming may benefit pasture growth by extending the growing season, so that there is projected to be a slight net increase in pasture productivity (Howden *et al.* 1999d; Crimp *et al.* 2002), but small increases in the length of the growing season and greater growth efficiency due to higher CO_2 failed to compensate for reduced moisture levels in central Queensland (Cobon *et al.* 2005a).

The general pattern of the impacts of climate change across the rangelands may therefore be that the least productive arid rangelands are the most negatively affected. Marginal pastoral enterprises in arid rangelands may be at the greatest risk of becoming non-viable under climate change. In contrast, the more productive eastern and northern rangelands are the most likely to provide opportunities for slight increases in productivity (Heyhoe *et al.* 2007). Rising temperatures are most likely to cause heat stress problems in the northern rangelands, but in the cooler, southern areas, some warming may be beneficial in extending the growing seasons.

Adaptation Options

Current options for dealing with climate variability

Australia's rangelands are characterised by high year-to-year variability in rainfall that, in turn, drives high variability in plant growth, nutrients available to livestock and availability of land management options (e.g., use of fire and spelling) (McKeon *et al.* 2004). Tactical reactive adaptive responses to short term climatic variability would automatically help to adapt an agricultural system to a longer term overlay of climatic change (McKeon and Howden 1992; Gifford *et al.* 1996; Cobon and Toombs 2007b). Analysis of historic relationships between climate variability and changes in pastoral land condition have shown that episodes of major degradation in Australian rangelands have often been associated with drought, that land can be degraded very rapidly, and that recovery of degraded lands is very difficult (McKeon *et al.* 2004). Climate variability therefore presents not only an economic challenge for managing variable enterprise profitability, but also a serious challenge to utilizing rangeland resources sustainably. The difficulty of this challenge is likely to increase with climate change and future increases in climate variability.

In many parts of Australia, much of the year-to-year variability in rainfall is associated with the El Nino-Southern Oscillation (ENSO) and the Interdecadal Pacific Oscillation (IPO) (McKeon *et al.* 2004). Based on these phenomena, operational seasonal forecasts have been developed using changing patterns in sea surface temperatures (Day *et al.* 2000). These statistical relationships are strongest (and therefore their forecasting utility is greatest) for the eastern third of Australia and are weakest for a north-south band running through eastern Western Australia. Using seasonal climate forecasts to adjust stock numbers is likely to be successful in climates where there is a high probability of extended droughts of more than 1 year (McKeon and Hall 2000). As the majority of grazing enterprises rely on a constant nucleus of breeders (cows or ewes) to maintain herd and flock populations (O'Rourke *et al.* 1992), there is limited flexibility to make rapid adjustments in stock numbers (McKeon and Hall 2000). Seasonal climate forecasts can benefit pastoral enterprises if they use a strategy of raising stocking rates by 20% in above average, use standard stocking rates in average years, and reduce stocking rates by 20% in below average years (Ash *et al.* 2007; McKeon *et al.* 2000; Stafford Smith *et al.* 2000; Cobon *et al.* 2005b).

It has been suggested that methods that adjust management practices to track year to year climate variability, will also automatically track climate change over several decades (McKeon and Howden

1992; Gifford *et al.* 1996). Tracking climate change could therefore provide a useful form of adaptation during the early stages of climate change, before climate events start to regularly fall outside the bounds of historic variation. Tools to assist pastoralists in tracking climate variability should therefore be enhanced and promoted as part of adapting to climate change.

A major issue is the uncertainty with regard to future rainfall projected under climate change. For example, CSIRO (CSIRO 2007) (page 65) indicated that 'regional precipitation variations can be quite sensitive to small differences in the circulation and other processes, as is evident from the large natural variability of precipitation over Australia. Different models may therefore simulate somewhat different rainfall changes. As with previous climate change projections, it will not be possible to make definitive statements on the direction of precipitation change in many cases'. In addition projected precipitation changes for 2050 and 2070 are larger and more sensitive to emission scenarios. The range of precipitation change in 2030 range from -10% to +5% in northern areas and -10% to little change in southern areas. CSIRO (2007) (page 68) noted that 'decadal-scale natural variability in precipitation is comparable in magnitude to these projected changes and may therefore mask, or significantly enhance, the greenhouse-forced changes'. Furthermore other human-induced climate forcings such as stratospheric ozone depletion, Asian aerosols and land cover change need to be considered in evaluating current trends and projections in rainfall (McKeon 2006; McAlpine *et al.* 2007; Burroughs 2003).

Not surprisingly graziers and their advisers faced with this continuing uncertainty as to the direction of projected changes in rainfall are likely to rely on either responding to immediate rainfall variability (e.g., the last five years) or including year-by-year responses incorporating seasonal climate forecasts. To some extent this approach may have allowed some adaptation since the 1980s as there have been a greater number of El Niño events compared to La Niña events (Power and Smith 2007). In Queensland, the perceived drying of Queensland grazing lands since 1950 has been consistent with historical variation in ENSO and inter-decadal indices of the Pacific Ocean (Crimp and Day 2003). (However, see "Maladaptations" below, for cautions in adjusting management based on experiences of recent climate fluctuations.)

There are other strategies for coping with climate variability that do not involve tracking climate variation. These include using a conservative, but constant, stocking rate from year to year; diversifying sources of income; and diversifying climate risk geographically by owning multiple pastoral properties in regions with different patterns of climatic variability. While these strategies would not necessarily provide the automatic benefit of tracking climate change, they may still be of adaptive value in increasing the capacity of pastoral enterprises to with future uncertainty.

Adaptation options for dealing with climate change

In order to adapt to climate change, pastoralists will need to change their management practices to take full advantage of new opportunities and minimize any negative impacts. At a national industry level, there are likely to be winners and losers, with some rangelands becoming more productive while others become less suitable for grazing. For the grazing industry as a whole, it may be possible to offset some of the losses in regions that are negatively affected by taking advantage of opportunities where rangeland productivity increases.). Monitoring trends in pasture production and quality, woody vegetation, pest and weed densities and animal production will raise community awareness and understanding of the impacts of climate change and foster development of adaptation strategies.

Below we discuss adaptation options against the major areas of land management that will be impacted by climate change (from the discussion above).

Managing pasture productivity and grazing pressure

To offset the negative effects of increasing temperatures and regional changes in rainfall, adaptation actions will need to focus on enhancing the benefits of CO_2 on resource use efficiency and extended growing seasons from earlier warming at the start of the growing season in southern climates. Traditional efforts to improve or increase forage productivity of native pastures in more humid rangelands have been achieved by removing of trees/shrubs, to increase the availability of water, nutrients and light for grass growth (Burrows *et al.* 1988). To counteract the tendency to woodier vegetation at present, and in the future (Burrows *et al.* 2002), it may become more desirable to use fire and selective thinning, to maintain current tree levels and pasture productivity. However, continued removal of tree/shrubs will remain a controversial adaptive strategy due to potential impacts on hydrology, biodiversity and greenhouse gas emissions, and may continue to be restricted by legislation.

In regions where rainfall is projected to decrease (e.g. southern areas of Australia) opportunities to improve pasture productivity will be limited and it is unlikely that it will be possible to maintain current productivity. This especially likely in temperate and Mediterranean native pastures where grazing has had the effect of decreasing woody species density, causing concerns for biodiversity conservation (Dorrough *et al.* 2006; Pettet and Froend 2000). Problems of declining pasture productivity with future drying in these regions are likely to be compounded by the need to increase woodiness of native temperate pastures for biodiversity conservation.

Additional adaptation strategies to maintain or enhance current forage production may include: (1) sowing new pastures which are better adapted to higher temperatures, higher CO_2 concentration, water constraints and changes in soil fertility; and/or (2) providing additional nitrogen through use of sown legumes (Lodge *et al.* 1984; Walker and Weston 1990). However, if new pasture species are to be introduced, it will also be necessary to consider risks of introduced species becoming weeds, impacts on biodiversity, and effects on soil acidity (for introduced legumes).

Current management, and particularly rehabilitation, of pastures requires careful grazing management including conservative stocking rates, strategic spelling and responsive adjustments to stocking rates based on seasonal climate forecasts (McKeon and Howden 1992; Johnston *et al.* 2000; Cobon and Clewett 1999; Cobon 1999). These practices will become more important with climate change and will be necessary to ensure desirable pasture species establish and are maintained as species ranges shift under climate change. Similarly, careful grazing management will be required to facilitate the establishment of any introduced species. With shifts to rainfall patterns that increase the risk of soil erroision, it will become increasingly important to ensure that ground cover is maintained in rangelands. It will be necessary to redefine safe carrying capacities, pasture utilization levels and grazing management practices.

Managing forage quality

In adapting to climate change, it will be important to consider changes in forage quality. In temperate pastures, there is generally insufficient metabolisable energy in fodder for protein to be fully utilised.

Increases in non-structural carbohydrates (the source of energy for the rumen) can therefore compensate for the declines in protein that occur with increasing CO_2 (Lilley *et al.* 2001b) or declining N availability (Peyraud and Astigarraga 1998). In sown pastures, breeding for grass varieties having high levels of non-structural carbohydrates has been able to compensate for reduced presence of legumes (Evans *et al.* 1996). Similarly, in temperate pastures it may be useful to breed for grass cultivars with high non-structural carbohydrate levels to compensate for reduced protein levels under rising CO_2. In the higher rainfall rangeland areas the use of introduced legumes can greatly increase the nitrogen input to, and productivity of both pastures and livestock, as could fertilizing pastures (although soil acidification and increased N_2O emissions need to be considered).

The above options may be useful in the most productive pastures, but are unlikely to be viable in extensively managed rangelands. In the latter case, pastoralists will likely to have to rely on increased use of feed supplements (N, P and energy) and rumen modifiers to compensate for declining forage quality. In rangelands that are close to grain-producing areas it may be possible to concentrate on utilizing pasture growth earlier in the season, destocking earlier, and to make greater use feedlots to finish livestock.

Managing pests, disease and weeds

Current methods for controlling pests and disease in the grazing industry include: applications of pesticide and chemicals to respond to outbreaks; strategic use of fire to control weeds; biological weed control; vaccinations to enhance resistance to existing pests and disease; and selection of tick resistant (*Bos indicus*) cattle in the northern Australia. Pesticides have proved useful in the past but they are likely to become less effective options in the future because of rising costs and resistance. Instead, developing improved predictive tools and indicators will provide opportunities to reduce reliance on pesticides. Quantitative modelling has proved particularly useful in managing cattle ticks in northern Australia by identifying areas and periods of greatest risk. Other options that could be developed to improve management of pests and diseases include identifying opportunities to introduce more species of dung fauna (to eradicate buffalo fly larvae), encouraging greater use of traps (buffalo fly and sheep blowfly) and vaccines (cattle ticks and worms). It will also be important to improve monitoring and border surveillance of pests and diseases whose ranges are currently limited by cold temperatures (e.g., flies and ticks). The introduction of new exotic pests such as screw worm fly would prove catastrophic for all mainland animal species. Climate change may give such a pest species the opportunity to establish in far northern Australia.

Woody weeds, particularly legumes in tropical rangelands, are likely to require more attention with climate change. Chemical and mechanical control would be more economically-viable under such conditions (Burrows *et al.* 1990). Where pasture productivity increases with climate change, there may also be opportunities for more frequent use of fire to control woody weeds. However, where pasture productivity declines under future climates, it will become more difficult to use fire as a management tool.

Animal husbandry and managing health

One of the greatest climate change challenges for the grazing industry will be its vulnerability to extreme temperatures and water limitation. Howden and Turnpenny (1997) and Howden et al. (1999a) showed that the incidence of heat stress has increased significantly since 1957 across large areas of

Australia. This would suggest that the practice of selecting cattle lines with effective thermoregulatory controls or adaptive characteristics within breeds, such as coat colour and conversion efficiency, would need to continue if current levels of productivity are to be maintained. This practice may need to become more common in more southerly regions as the frequency of heat stress days increases. Additional adaptation strategies such as modifying the timing of mating could also serve to match nutritional requirements of cow and calf to periods with favourable seasonal conditions. This means that the animal production system (cow/calf steer trading, finishing for market) would have to become more flexible in order to accommodate potential changes to climate variability (McKeon *et al.* 2004), including changes in timing of supplementation and weaning (Fordyce *et al.* 1990).

In some grazing enterprises such as feedlots, the construction of shading and spraying facilities may represent an economically feasible adaptation measure (see following chapter intensive livestock). In areas that may experience greater extremes this option will be of particular value. It may also be necessary to plant plots of suitable shade trees, and increase the number of water points. In areas that become more prone to flooding it will also be important to provide livestock with access to areas of higher ground.

Barriers and synergies to adaptation

As confidence in climate change projections grows and trends in observed weather data become more apparent, the motivation for adaptation in the grazing industry will increase. However, the adoption of new property management practices will require: (1) confidence that climate change can be separated from the naturally high year-to-year climate variability inherent in these production systems; (2) the motivation to change based on the perceived risk and opportunities of climate change, (3) establishment and implementation of applicable new technologies and demonstration of their benefits; (4) buffering against establishment failure of new practices during less favourable climate periods; (5) alteration of transport and market infrastructure to support altered production (McKeon *et al.* 1993), and (6) development and modification of government policies and institutions to support implementation of the required changes.

Government, at all levels, is continually developing and modifying strategies, initiatives and policies to deal with environmental issues such as land condition, biodiversity, greenhouse gas emissions, drought, salinity and water quality. While some of these policies are compatible with promoting adaptation to climate change, others will serve as disincentives and barriers to adoption of recommended practices. Similarly, management practices in the grazing industry are constantly being adapted to an ever changing operating environment. At present, management practices are changing in response to influences such as shifting rural population densities, reduced on-farm profitability, changes in government legislation for drought relief, and enforcement of legislation on resource management and animal cruelty (McKeon *et al.* 1993). Some of these changes will prepare pastoralists for climate change, while others will hinder adaptation efforts. It will be important to identify and promote any synergies with existing initiatives and address any conflicts that create barriers to adaptation.

The Australian Federal Exceptional Circumstances drought scheme provides welfare, and interest rate subsidies for the duration of a drought-declared period, and for a further year after revocation, thereby making the scheme more sensitive to the duration of, rather than, the frequency of droughts (Pittock *et al.* 2001). State drought schemes, such as in Queensland, are more sensitive to the frequency rather than duration of drought (Pittock *et al.* 2001). For this reason, if Australia's climate does change towards drier conditions, more frequent and longer drought declarations will occur under the current drought policies (Pittock *et al.* 2001). This may, as has been the case in both the wool and sugar industries, catalyse a shift in policy from that of support to facilitation of restructuring (Pittock *et al.* 2001).

Similarly initiatives and strategies in place to encourage reductions of greenhouse gas emissions, sequestration and potential trading of carbon (e.g. Greenhouse Gas Abatement Program and Greenhouse Challenge) may represent synergies for exploring changes to on-farm management. Recent studies (Burrows *et al.* 2002; Henry *et al.* 2002) in northeast Australia have indicated that regrowth in grazed eucalypt woodlands (60M ha) accounts for a sink of approximately 0.53 t C ha^{-1} yr^{-1} of above and below-ground biomass. For this reason, if carbon becomes a tradeable commodity, loss of productivity from reduced land-clearing may be temporarily offset by gains in tradeable carbon stocks if an acceptable C-accounting methodology can be cost effectively instituted. There may be further opportunities for carbon sequestration in soils, particularly through recovery of degraded rangelands where past overgrazing has depleted soil carbon.

There are many existing initiatives that promote sustainable use of rangelands by encouraging stewardship of natural resources and developing the capacity to cope with variable climate and other uncertainties and changes affecting business operations. It will be important to incorporate considerations of climate change into these existing initiatives to further enhance the capacity of the grazing industry to prepare and implement adaptation strategies.

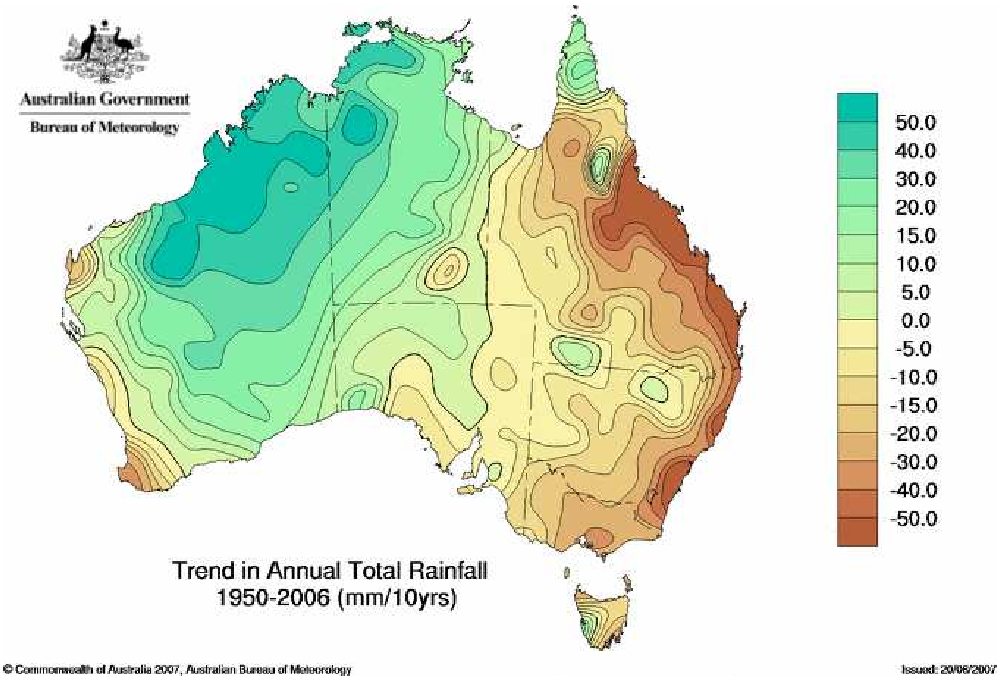
Risks of maladaptation

There are several situations in which responses aimed at dealing with specific aspects of climate change could have unintended negative consequences when viewed in the broader context of land management and climate change adaptation. We highlight some of these risks of maladaptation below.

The proposal discussed earlier for adapting to the early stages of climate change is to enhance and increase the adoption of strategies to adjust management actions (particularly stocking rates) to climate variability using seasonal climate forecasts. Some problems may exist with this approach given current levels of forecast skill and challenges that still exist in extending seasonal climate forecasts out beyond the 6 month period.

However there is a striking incongruity between trends in rainfall across Australia over the past few decades (Figure 9.3) and future projected trends under climate change (Figure 1.3). This raises concerns about potential maladaptation. Where multi-year and multi-decadal cyclical patterns of climate variability are in a phase that is opposite to long-term climate change trends, this could encourage land managers to rely more on practices that will not be appropriate under longer-term climate change. For example, there has been a wetting a trend in north-western Australia over the past fifty years (Figure 9.3) and some pastoralists in this region have taken advantage of increased pasture production by moving towards more intensified livestock production systems (Ash *et al.* 2006). However, these trends may reverse with climate change over the next 30 to 70 years, with projected drying and warming across much of central and northern Western Australia (Figures 1.2 and 1.3). In such situations, changes to enterprise management that have been made to take advantage of the temporary favourable conditions may leave pastoralists more poorly prepared for longer-term drying. Future use of tools for dealing with climate variability should therefore take climate projections into account so that decisions to take advantage of temporarily favourable opportunities can be balanced against preparing for longer-term impacts of climate change.

Figure 9.3: Trends in observed annual rainfall from 1950 to present (www.bom.gov.au)



One option for offsetting declines in forage quality under climate change would be to introduce legumes into native pastures. This might seem particularly attractive since higher CO_2 levels are expected to favour legumes over grasses for dry matter production and reproductive effort (Ainsworth and Long 2005; Jablonski *et al*. 2002). However this benefit needs to be considered carefully together with the risk of soil acidification that the introduction of legumes brings. There are also locations where introduced legumes (e.g., seca stylo) have enabled livestock to drastically reduce the grass component of pastures, creating legume monocultures. More generally, caution needs to be exercised in other proposed solutions to improve pastures by introducing species/varieties that are hoped to be superior under altered climate conditions. The past history of introducing desirable species to pastures has not always been successful, with some species becoming weeds, reducing biodiversity or otherwise negatively affecting ecosystem health.

There are several situations related to greenhouse gas emissions in which adjustments that land managers make to deal with climate change could have negative consequences. In rangelands where woody weed invasions and vegetation thickening increase under climate change, managers might consider increased use of fire to control the problem. However, this would increase the emission of nitrous oxide, a powerful greenhouse gas. There would also be an increase in GHG emissions from methane if livestock production is intensified in areas that are favourably affected by climate. Efforts to curb GHG emissions through trading schemes could also provide opportunities for carbon sequestration in rangelands, particularly savannas, if adequate C-accounting methodologies can be devised. The short-term benefits of participating in these schemes need to be balanced against longer-term effects on the pastoral productivity. For example, some forms of carbon sequestration, such as managing land for increased woody vegetation, would have an ongoing negative impact through a decline in pasture production. There is also the risk that increased stores of sequestered carbon in rangelands may not be sustainable as the climate changes, particularly in locations that become drier (or from wildfire), and the later depletion of these stores would create carbon emission liabilities for land owners.

In developing sound climate change adaptation strategies it will be important to consider not only the direct, intended benefits of proposed actions, but also the broader, unintended consequences (both positive and negative) of those actions.

Costs and benefits

To date there have not been any comprehensive analyses of the costs and benefits of climate change impacts to the pastoral industry, nor of the costs and benefits of adaptation measures to offset these impacts. There have been some modelling studies have been conducted to determine the likely impacts of climate change on pasture production in different rangeland regions. In addition, (Howden *et al.* 2003) assessed the economic trade-offs between production and carbon sequestration if pastoralists were to engage in carbon trading. But there has been no assessment of costs of developing and implementing adaptation strategies and the benefits these could yield in reducing the impacts of climate change or exploiting new opportunities.

In the short-term, the most cost-effective adaptation strategies may be to identify synergies with existing natural resource policies, and promote actions that provide dual benefits for current land management and future preparedness for climate change. However, such incremental strategies may be insufficient where transformative changes in land use are required, either because grazing becomes non-viable or where new opportunities emerge. These more substantial adaptation measures will be important to fully adjust to climate change, but will be more costly implement (and likely to become more costly and difficult the later decisions are delayed).

Knowledge Gaps and Priorities

Over the past twenty years there have been many studies of the potential impacts of climate change on the grazing industry, but these have tended to focus on individual components of the problem. For example, studies have tended to focus on individual aspects of climate change (rainfall, temperature or CO_2), individual impacts (e.g., heat stress, pasture production or woody encroachment) and specific geographic locations in the rangelands. Such studies have been necessary to build a base understanding of some of the individual components of climate change responses, and focussed investigations will continue to be essential for filling knowledge gaps. Many discrepancies in results, which need resolution, have been identified in the above discussion. Much remains to be done at that base level in the system hierarchy. But, to properly inform decisions on adaptation, it is also necessary to combinine these individual components of climate change and the production system. Below we outline some of the steps that will be required to build more a comprehensive, cross-regional understanding of the broad suite of climate change impacts on the grazing industry.

1) Systems description of the grazing industry

Existing knowledge needs to be synthesised to express the grazing industry as a production system with a flow of materials (e.g. rainfall, irrigation, carbon, energy, plant growth, animal products) including land use/location, bio-physical constraints (disease, pests, terrain) and other factors (water demand, greenhouse gas emissions, and exchangeable value (in dollar terms)). In addition, the dominant climatic impacts, including past experience of climatic variability (e.g. drought in grazing lands), need to be clearly identified.

2) Modelling impacts of climate change

As a starting point for adaptation, it will be necessary first to clearly define the challenge to which solutions are being sought. This requires quantifying the range of plausible, but uncertain, impacts that the grazing industry could be exposed to under climate change. The recent IPCC report (IPCC 2007) highlights how poorly the impacts of climate change have been studied in Australia compared to other parts of the world.

a) Systems models: Property level models need to be developed to include the direct, indirect and interactive effects of climate, atmospheric CO_2 concentration and land management. In addition, there is a need to develop forecasting schemes that incorporate long term climate change trends to allow management options to be explored at seasonal and multi-seasonal timescales.

b) Greenhouse gas linkages: The current linkages between industry models and national greenhouse gas inventories should be enhanced to allow the grazing industry to be evaluated in terms of greenhouse gas emissions and carbon sequestration. This will become particularly important if the grazing industry wants to evaluate participation in carbon trading schemes.

c) Standard climate scenarios: Efforts need to be made to produce a commonly-utilised set of scenarios suitable for property scale and nationwide modelling efforts. This should include the provision of downscaled climate changes scenarios in the same form as historical climate data.

d) Standard site parameterizations: Similarly, modelling efforts would be assisted by developing a set of standard site descriptions (ecological parameterizations of current soils, vegetation and climate) to represent each of the different types of rangeland in the country.

e) Aggregating to national scale: The modelling capability needs to be developed to apply/aggregate property-scale models to regional and continental production scales. These aggregated models need to be able to estimate national impacts of climate change for specific aspects of the grazing industry, including effects of soils, terrain, and uses existing enterprise management. These models should also be able to identify where and under what conditions existing enterprises become marginal or fail.

3) Expand current adaptation options (Incremental change)

Once the adaptation challenge has been clearly identified, a set of adaptation options need to be developed to address the range of plausible impacts that the grazing industry could face. As a first step, graziers and policy makers should be consulted to determine what their immediate reactions to these impacts would be. A comprehensive evaluation of the full costs and benefits of these responses would reveal which behaviours would provide genuine adaptation benefits, which were maladaptations, and where modified or alternative adaptive responses would be more appropriate.

4) Explore alternative industries (Transformative change)

Compare alternative land uses/industries/commodities and calculate the effect of optimising land use/commodity choice. This procedure should show where alternative land uses overlap (e.g. cattle and grain), where the viability of pastoral enterprises may be threatened, and where grazing may become more suitable than existing land uses after climate change. It will be important to identify regions where changes in land use are required, because these will present some of the biggest challenges for adaptation.

5) Improve current monitoring of components of the grazing industry

Improve current monitoring systems that are able to provide insight into changing grazing pressure, carrying capacity, pasture production and water availability. These should reveal any trends towards deterioration of natural resources or enterprise performance, allowing early remedial action, thus encouraging a more robust grazing industry with better adaptive capacity to climate change: for example, improvement in current real-time climate and degradation alert systems such as AussieGRASS (Carter *et al.* 2000).

6) Facilitating adoption

Communities will need to be supported in adapting to climate change, particularly where socioeconomically disruptive transformative changes are required. This will require that appropriate adaptation strategies are developed and that supporting policies and institutions are put in place. In addition, information regarding both the potential impacts of climate change and potential adaptation strategies will need to be effectively disseminated to, and implemented by pastoral managers and policy makers (e.g., through GLM workshops).

Grazing will continue to play an important role in shaping Australia's economy and land use over the coming decades. Significant contributions to sustainable management have resulted from efforts to better understand grazing ecology, grazing practices and productivity (Quirk 2002). Climate change is adding another dimension to the existing challenges facing grazing enterprises. To assist with priority-setting in addressing this challenge, the adaptation options discussed in this review have been summarised below (Table 9.1). Adaptation options that are already well assessed have been identified, along with their feasibility and immediacy, and priority knowledge gaps that need to be filled. By developing and implementing adaptation measures through existing initiatives aimed at improving the sustainability of pastoral enterprises and there capacity to adapt to change, we will be able to better prepare the grazing industry for the challenges that lie ahead.

Table 9:1: Summary of climate change adaptation options for the grazing industry indicating whether the option 1) has already been assessed or is a remaining knowledge gap, 2) is highly feasible, 3) would be feasible / effective immediately, or 4) should be a high priority for research, assessment and implementation in developing adaptation strategies.

Adaptation options	**Options already assessed**	**Options with high feasibility**	**Immediacy**	**Priority activities**
Broad scale adaptation				
Define the adaptation challenge by describing the (uncertain) range of impacts that could affect pastoralists under a range of plausible climate change scenarios.	X	✓	✓	✓
Obtain feedback on the immediate management responses that producers would be likely to employ to deal with impacts (above point).	X	✓	✓	✓
Obtain feedback on the immediate policy responses that policy makers would be likely to employ to deal with impacts (above point).	X	✓	✓	✓
Encourage linkages with existing government policies and initiatives e.g. GGAP, Greenhouse challenge, salinity, water quality	X	✓	✓	✓
Modification of existing Federal and State Drought Schemes to encourage adaptation	X	✓	✓	✓
Introduction of ISO standards to grazing enterprises that acknowledge climate change adaptive management strategies	X	✓	X	X
Ensure adequate buffering against establishment or adaptation failure	X	✓	✓	✓
Altering transport and market infrastructure to support altered production	X	X	X	X
Improved water management at the on-farm scale	✓	✓	✓	✓
Pasture productivity and grazing pressure				
Redefine safe stocking rates and pasture utilization levels under climate change	X	X	X	X
Diversification of on-farm production	✓	✓	✓	✓
Expand current area of grazing potential	✓	X	X	X
Expand routine record keeping of weather, pest and diseases, weed invasion and outputs	X	✓	✓	✓
Introduce software for use by producers to interpret grazier records	X	✓	✓	✓
Increase sowing of new pastures	✓	✓	X	X
Selection of sown pastures better adapted to higher	✓	✓	✓	X

Adaptation options	Options already assessed	Options with high feasibility	Immediacy	Priority activities
temperatures and water constraints				
Provision of additional nitrogen through sown legumes	✓	✓	✓	X
Provision of phosphates to both improved and unimproved pasture *(but well assessed in southern regions)	X*	X	X	X
Provision of urea and phosphates directly to stock via reticulation *(not assessed on a large scale)	X*	✓	✓	X
Greater utilisation of strategic spelling	X	✓	✓	✓
Introduction of responsive stocking rate strategies based on seasonal climate forecasting	X	✓	✓	✓
Development of regional safe carrying capacities i.e. constant conservative stocking rate	✓	✓	X	✓
Development of software to assist pro-active decision making at the on-farm scale	✓	✓	✓	✓
Pests, ferals, diseases and weeds				
Improve pest predictive tools and indicators	✓	✓	✓	✓
Improve quantitative modelling of individual pests to identify most appropriate time to introduce controls	X	✓	✓	✓
Increased use of biological controls	X	✓	X	X
Increased use of insect traps	X	✓	✓	X
Incorporation of alternative chemical and mechanical methods for reducing woody weeds	X	✓	✓	X
Animal husbandry and health				
Selection of animal lines that are resistant to higher temperatures	✓	✓	X	✓
Modify timing of mating based on seasonal conditions	✓	✓	X	✓
Modify timing of supplementation and weaning	✓	✓	X	X
Construction of shading and spraying facilities	✓	X	X	X
Increase use of trees as shading and reducing wind erosion	✓	✓	X	X

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10: INTENSIVE LIVESTOCK INDUSTRIES

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Key Messages:

- Increased climatic variability, including changes in rainfall, will challenge traditional dairy production systems.
- Warmer and drier conditions are projected for most intensive livestock producing regions, raising the likelihood of heat stress conditions.
- Enterprise level adaptation needs to be complemented by policy level analysis and possible reform.
- Enterprise and policy level adaptation options should be developed and tested through comprehensive systems analysis
- Traditional high energy and water use options for improving the environment of livestock under higher heat stress conditions are likely to be mal-adaptive. Low energy options should be identified and evaluated.
- Competition for feed stock may increase as options for biofuels and international food markets increases.

Introduction

Dairy

The Australian dairy industry is the third most important rural industry behind beef and wheat, valued at $3.2 billion in 2006/07, and the fifth most important agricultural export, valued at $2.5 billion (Australian Bureau of Statistics). The bulk of milk production occurs in Victoria (approximately 65%), although all States have viable dairy industries that supply fresh milk to nearby cities and towns. The industry occurs within eight administrative dairy regions, established for the purposes of targeting research, development and extension (Figure 1):

- Subtropical Dairy; extending from Kempsey in NSW to the Atherton Tablelands in Far North Queensland.
- Dairy Industry Development Company (DIDCO); covers the eastern fringe of New South Wales.
- Murray Dairy; the largest dairying region in Australia, straddling the Murray River from the Alps to Swan Hill. It covers the Northern Irrigation and North-East regions of Victoria and the Riverina and Upper Murray regions of New South Wales.
- GippsDairy; covers the Gippsland region, Victoria.
- WestVic Dairy; covers the south-west of Victoria.
- DairyTas; Tasmania.
- DairySA; South Australia.
- Western Dairy; the majority of farms occur in coastal south west Western Australia.

Milk production is largely based on pasture-systems that are affected by seasonal rainfall and temperature patterns, although a significant proportion is on irrigated pasture. Farms range from low input to high input across the country, with calving occurring both seasonally and year-round. An increasing number of farmers are supplementing pasture feed with other feedstock, such as grain and sorghum, and dairy feedlots are also increasing as a consequence of the current drought. Farms in the Murray Dairy region are highly productive, given the Mediterranean climate, proximity to grain growing regions, and access to a reliable supply of water for irrigation, although this reliable water supply may change.

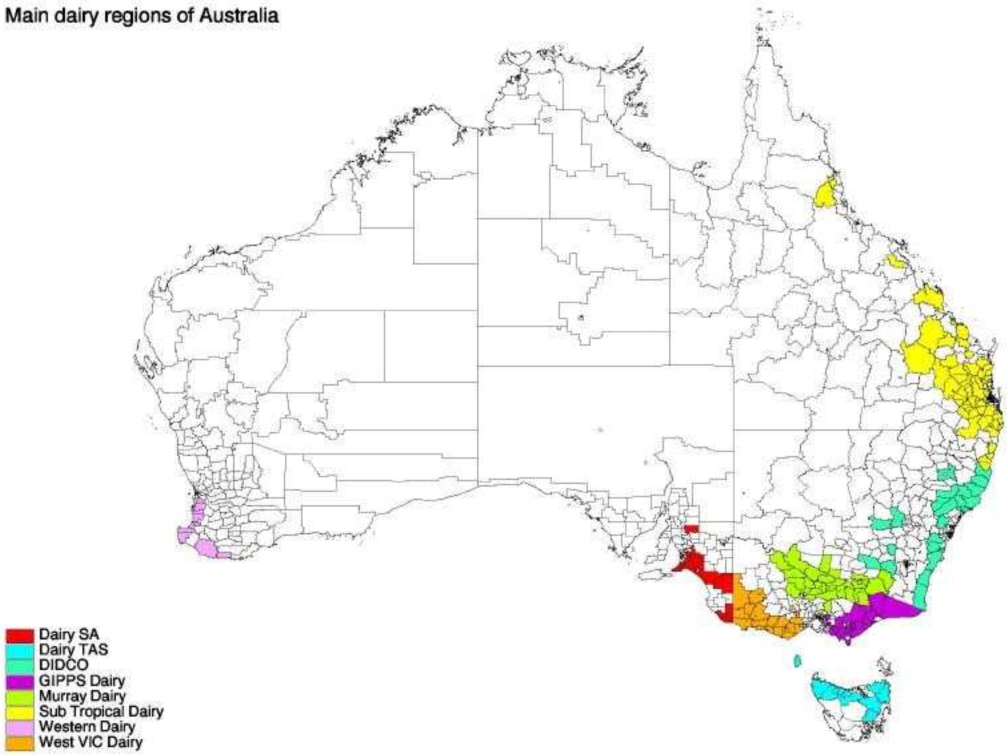

Figure 10.1: Location and distribution of the eight Australian dairy regions (*Source*: Dairy Australia).

Pigs

Pig production occurs in approximately 2,800 farms spread across all States of Australia, with the highest proportion of producers located around the grain, sorghum or maize-growing regions. For example, 30% of Queensland's producers are located on the Darling Downs, an extensive grain producing region (Source: www.dpi.qld.gov.au/pigs). Intensive piggeries usually house their animals indoors for the duration of their life, in specialised sheds. Approximately 50% of Australia's pigs are raised in deep litter housing systems and/or Ecoshelters®. These sheds tend to use passive end to end ventilation systems, with some having cross flow options. Free range piggeries run their animals in paddocks that have rooting areas, wallows, and huts for shelter. Climatic and soil conditions limit the suitability of many areas for free range farming, for example, as temperatures cannot be kept below 27º C.

Poultry

The Australian poultry industry is primarily focussed on chicken meat (broiler) production and egg production. There are a small number of turkey and other fowl producers; the issues and options raised here are likely to be similar to chicken production, but are not explicitly considered here.

Chicken meat production is becoming increasingly regionalised, following initial development near the major capital cities (*Source*: www.poultryhub.org):

- New South Wales - Outer metropolitan Sydney, Central Coast, Newcastle, Tamworth, Griffith, Byron Bay

- Queensland - South East Queensland
- Victoria - Mornington Peninsula, east Melbourne, Geelong, Bendigo
- South Australia - Outer metropolitan Adelaide, Two Wells
- Western Australia - Outer metropolitan Perth
- Tasmania - Outer metropolitan areas
- Northern Territory - No commercial farms

Breeding farms owned by the integrated meat companies are located away from traditional poultry rearing areas to reduce disease risks. Grow out farms, where chickens grow from day-olds until they are ready for processing, are generally within 100km of the processing plant, and require a guaranteed feed source, guaranteed water supply and guaranteed three phase electric power. Most vertically integrated companies own feed mills, with their location driven by transport costs of feed ingredients and proximity to the farms.

The majority of commercial grow-out farms are intensive and highly mechanised, with the chickens raised in large open sheds. These sheds tend to be large, with 3 to 10 sheds per farm, holding 40,000 to 60,000 chickens per shed. Shed temperature, humidity and air quality are carefully controlled and regulated.

Egg production and supply to the Australian market is largely met by 423 companies (ABS 2005), located largely around major metropolitan or regional centres and with easy access to feed stock. Farms range in size, with the largest having between 100,000 and 500,000 hens contained in multiple level sheds, although many will not have more than 20,000 birds. There is an increasing number of free range or barn raised egg farms due to consumer preferences or perceptions around animal welfare. As with chicken meat farms, shed temperature, humidity and air quality are carefully controlled and regulated, and a guaranteed supply of water is required (*Source*: www.poultryhub.org).

Feedlots

Beef feedlots are concentrated in the major agricultural regions of Australia where they have adequate supplies of cattle, water, grain and other feedstuffs. The majority are in southern Queensland and New South Wales. At last estimate available to the authors there were around 600 accredited feedlots, with some 860,000 head of cattle (Australian Lot Feeders Association Overview 2002). Regional and annual climatic variability, and product quality assurance, have driven the use of feedlots for growing beef, in preference to pasture or rangelands.

An increasing number of dairy farmers are utilising feedlots to supplement or replace their reliance on pasture, particularly in south east Queensland. Some farmers are also buying up grain producing properties in order to help ensure a reliable feed supply.

Climate Change Impacts

Climate projections for Australia in 2030 indicate a warming of about 1ºC relative to the average temperature from 1980-1999. The degree of warming is expected to be less in coastal areas and higher inland. The majority of climate models indicate decreased rainfall over the next 20 years, with decreased annual average and winter rainfall in southern areas, decreased spring rainfall in southern and eastern areas, and autumn decreases along the west coast. Little change is projected for rainfall in the far north. Specific projections for the dairy regions of Australia in 2030 indicate that climatic conditions will be warmer and drier, resulting in increased evaporation and reduced runoff (Hennessy 2007). Temperatures are projected to increase between 0.4 to 1.5 ºC, with increased maximum temperatures in southern Australia and increased minimum temperatures in northern Australia. The greatest declines in rainfall are projected to occur in spring and winter.

The impacts of climate change for intensive livestock production in Australia are likely to be both direct and indirect. The direct impacts are those which act explicitly on the stock or management unit, such as heat stress reducing productivity. Indirect impacts are those which act on necessary elements of the production system, but are outside of the control of the farmer. These may include reduced water supply and increased prices or regulation, or a carbon tax on carbon emitting energy production.

A significant direct impact of climate change on intensive livestock is likely to be heat stress (Howden and Turnpenny 1997). Heat stress is a function of air temperature, relative humidity, air movement, and solar radiation. An animal suffers heat stress when it is unable to cool itself, or thermoregulate, to within its thermal tolerance levels, and this is a major issue for livestock production in the warmer parts of the world. Below a lower critical temperature an animal must increase its metabolic rate and activity (e.g. shivering) to maintain body temperature, while at the upper critical level the animal must expend energy (e.g. through ear flapping and panting) and water in order to cool. Animals respond to heat stress in a number of ways including: 1) reduced feed intake, 2) increased water intake, 3) changed metabolic rate and maintenance requirements, 4) increased evaporative water loss, 5) increased respiration rate, 6) changed blood hormone content, and 7) increased body temperature.

Heat stress results in significant economic and production losses for dairy operations throughout the world as, even with low humidity, when the temperature exceeds 27ºC the effective temperature is above the comfort zone for high producing dairy cows (Aharoni et al. 2005). One of the unintended consequences of achieving improvements in milk yield through selective breeding is that it is more difficult for cows to thermoregulate, even in temperate areas (Hansen 2007). This simply results from high productivity generating large amounts of metabolic heat which needs to be shed so that the animal can maintain body temperature at acceptable levels. Along with reduced productivity, heat stress also reduces the reproductive success of cattle (García-Ispierto et al. 2007), pigs (Wettemann & Bazer 1985) and poultry (Cooper & Washburn 1998). It has been suggested that a 1ºC rise in mean temperature will mean that passively ventilated or free-range pig production units may no longer be viable in the eastern states.

One commonly used measure of heat stress is the Temperature-Humidity Index (THI; Johnson et al. 1963) which has been shown to be a robust predictor of heat stress in cattle, and is related to reduced milk production in dairy cattle (Hahn and Oosburn 1969), conception rates (Hahn 1981) mortality rates (Hahn 1985), and distribution of beef cattle varieties in Africa (King 1983). It is used operationally for heat stress assessment in dairy cattle in South Africa (Du Preez et al. 1990). The THI is commonly used to indicate the degree of stress on dairy cattle, with a reading over 72 indicating the potential for heat stress and higher readings associated with progressively more negative impacts. While humidity may decrease in some situations under climate change, increases in temperature are likely to lead to increases in heat stress and the frequency of heat stress in almost all instances (Howden & Turnpenny 1997, Howden et al. 1999).

Another significant issue is that climate change is likely to impact on the quality, productivity and composition of pasture and will also affect the quality and productivity of crops and the locations in which they can be successfully grown (Tubiello et al 2007). CO_2 enrichment is known to increase plant biomass, yield and water use efficiency although there is a decrease in protein content. It also favours C_3 grasses over C_4 grasses, a compositional change that is generally positive for dairy production. However, in terms of pasture composition, the positive effects of CO_2 enrichment are likely to be counteracted through increased temperatures and reduced rainfall. C_4 grasses are likely to be favoured over C_3 grasses in a warming environment, with the increased water efficiency potentially reducing the impact of drier conditions to a small degree. The balance between these two alternating processes is likely to be situation dependent and is not well understood at present (e.g. Howden et al. 1999b).

Increased temperatures and reduced rainfall will increase demand for livestock drinking water (Howden and Turnpenny 1997), irrigation, or water for evaporative cooling. This is likely to occur in a political and market environment where water allocation from aquifers or waterways is more strictly controlled and regulated than it has been in the past, and where the cost of water is greater than it currently is. Intensive livestock farming is also likely to be competing with urban water demand, where the urban market can afford to pay more for the same unit of water.

Climate change is also likely to result in increased competition for supplementary or total feed stock between farmers, and between farmers and other markets for the same product. Farmers are already concerned about the potential for the biofuel market to reduce the supply of feed stock. The move towards more biofuels is likely to be driven by the need to reduce the use of fossil fuels as a climate mitigation measure, although this also has the potential to be a maladaptation.

The energy demand for climate control in production units where livestock are farmed in indoor climate controlled conditions is likely to increase. The majority of this energy is generated by coal fired power stations, and is likely to incur a carbon tax of some kind, adding to the cost of energy. There is also likely to be competition for peak supply with residential users and other industries, potentially resulting in brown-outs in some areas if generating capacity is not increased to cope with increased demand.

Adaptation Options

Current Options for Dealing with Climate Variability

The current options for dealing with climate variability in the intensive livestock industry are:

- Intensification of irrigation systems to maximise water use efficiency.
- Agistment of stock outside of the region where necessary.
- Shift from perennial pastures to a mix of annual and perennial pastures.
- Increase forage cropping.
- Use of feedlots.
- Supplementary feeding with grains or other feedstock.
- Ownership of feedstock producing farm.
- Maintenance or reestablishment of shelter trees.
- Changing calving patterns.
- Genetic selection for heat tolerant phenotypes.

- Climate controlled production sheds through mechanical or natural air conditioning.
- Naturally ventilated production sheds.
- Heat abatement through water misting and evaporative cooling of stock.

Adaptation Options for Dealing with Climate Change

These adaptation options have not necessarily been assessed for efficacy, practicality or cost effectiveness. Rather they are identified as options for further consideration, and are not listed in any particular order of priority.

Option 1 Increasing landscape resilience through revegetation and rehydration

Agricultural development has relied heavily on the clearance of native woody vegetation and the draining of wetlands. While this has resulted in significant economic returns nationally, it has reduced the capacity of agricultural land to cope with and recover from events such as droughts and floods. The natural capital of the land, its soils and water holding capacity, have been degraded and the impacts of this for agriculture are likely to be exacerbated under the climate change projections.

While research is needed to identify the most appropriate configurations, the resilience of agricultural landscapes to climate change can be enhanced by strategic revegetation and the recreation of wetland systems. For example, Ryan (2007) has shown that it is possible to reduce stormwater velocities and runoff, and hence erosion, while increasing infiltration and soil recharge by dissipating water flow through the strategic placement of tree belts on hill slopes currently covered with grass. Such revegetation can also provide immediate shelter from solar radiation for stock and equable microclimates, while at larger scales may also affect regional climates and precipitation regimes (Avissar and Pielke 1991; Pielke 2001, Pielke et al. 2007, Pitman et al. 2004).

The drainage of wetlands of all types to increase pasture cover, and the removal of impounding debris from streams and waterways, has resulted in a reduction in the capacity of soils to retain or store water, particularly during dry periods. Consequently irrigation is required; in many instances this water is drawn from aquifers or streams whose recharge or baseflow is contingent on wetlands retaining water in the landscape (e.g. Evans 2007). Irrigation water is also increasingly saline in many agricultural areas. Wetlands also provide ecosystem services in the form of mitigating or attenuating flood flows and through trapping eroded soil and leached nutrients.

While this is largely a catchment scale issue, a small number of horticultural production units have or are about to utilise wetland recreation to, amongst other things, reduce reliance on depleting or saline aquifers and maintain soil moisture during dry conditions (Pat Byrne, Best Results Pty Ltd, personal communication 2007). There is no reason why this could not be assessed and/or implemented for dairy production systems.

Option 2 Summer housing for dairy cattle

It is possible that the frequency of heat stress conditions in many regions may affect productivity to the degree that it is no longer profitable to run dairy cows on pasture, particularly during summer. In many cold regions of the world, cattle are housed indoors during winter where the climatic conditions can be controlled. The converse, i.e. housing dairy cattle indoors with a controlled climate during summer, may become necessary in some areas to ensure sustained productivity. This feedlot model for dairy is not necessarily a desirable or practical adaptation and, as with other options, would require a comprehensive benefit-cost analysis.

Option 3 Altered farm management

Howden et al (2007) identify a number of enterprise level management options for adapting practices to climate change. These are:

- Matching stocking rates with variable pasture production
- Rotational grazing and pasture spelling
- Modification of grazing times
- Timing of reproduction
- Alteration of animal or forage types
- Altered integration within mixed livestock crop systems
- Ensuring adequate storage of water
- Use of supplementary feeds.

A number of these options are already standard practice on dairy farms across Australia. Dairy farmers in the south of Australia are also applying techniques from north Queensland for dealing with heat stress. The most important aspect is to identify and evaluate options that increase the capacity of farmers and farming systems to cope with or take advantage of increased climatic variability and external economic dynamics, including shocks.

The use of shelter and shade where dairy cows are farmed in feedlots is essential, and techniques such as using sprinklers, misters, or shade cloth to keep the animals cool are desirable. However humidity may be increased by the use of evaporative cooling techniques, which adds stress to the animals, so there is a need to ensure adequate air velocity through the area (Berman 2006). It has been suggested that night feeding of cattle in feedlots may reduce the energy expenditure associated with foraging during the heat of day and result in sustained milk yield over time (Aharoni et al. 2005).

Option 4 Redesign of buildings for passive cooling

The energy demand for cooling in production sheds can be reduced by applying new building designs or materials (e.g. Raman et al. 2001). This can be a capital intensive option, but the energy cost savings achieved through retrofitting existing sheds may offset the capital outlay. New sheds should be designed and built with passive cooling and heating as the key driver, to be supplemented by active air conditioning where necessary.

Option 5 Supplementary or complete power generation onsite

Advances in photovoltaic technology are bringing down their cost and significantly increasing their efficiency and capacity to generate electricity (Green 2006). Production sheds and other buildings often provide suitable sites for photovoltaic cells which can supplement or completely supply the electricity needs for livestock production. This type of power source will also be providing peak power at the time of peak demand for cooling: a time when potential competition for energy and hence energy prices are greatest.

There are also other options, such as wind power, or co-generation using effluent and waste feed stock, for onsite generation of electricity.

Option 6 Clustering of compatible industries

Clustering of compatible industries with intensive livestock production, in order to tighten or close the resource loop, is another option. Agricultural industrial parks that co-locate industries involved in waste processing, energy generation, water capture and recycling, feedstock and foodstuff manufacture etc with livestock production have the option to reduce energy demand from fossil fuels and increase value in the value chain.

The siting of these agricultural industrial parks should be determined after considering the potential for increased exposure of the site to climate change.

Risks of Maladaptation

There are a number of risks of maladaptation to climate change in intensive livestock farming. The greatest risk is increasing reliance on fossil fuel based energy and water intensive solutions. This is likely to reduce the resilience of the industry to energy or water shocks, as well as adding to the problem of emissions and reduced water availability. Other adaptation options are likely to impact on the financial viability of the enterprise. For example, genetic selection for high producing dairy cattle has reduced their capacity to thermoregulate and cope with increased temperatures; conversely selecting for heat tolerant phenotypes can reduce productivity (Hansen 2007).

It is important that adaptation options be tested through multi-scale systems analysis so that the negative and positive feedbacks resulting from the proposed adaptation options can be explicitly identified. Dairy Australia is in the process of engaging in this form of analysis with stakeholders and participants in the Australian dairy industry.

The siting of new enterprises should consider the increased risk of exposure to climate change. For example, siting new enterprises in the north of Australia or in areas where water supplies are likely to diminish is maladaptive.

Costs and Benefits

To our knowledge there are few cost-benefit analyses of adaptation options for dealing with climate change and intensive agriculture. We consider that cost-benefit analysis is an integral component of assessing the value or utility of adaptation options, particularly those recommended at an industry level. A cost-benefit analysis was recently conducted to evaluate salinity mitigation measures for the Mary River (McInnes 2004), and the method used has been proposed as the benchmark method for future cost-benefit evaluations of projects involving environmental change.

The most relevant cost-benefit analyses relating to intensive livestock farming that we could find focus on the issue of heat stress management. We acknowledge that heat stress management is not necessarily the highest priority adaptation option for dairy. Davison et al. (1996) used cost benefit analysis to show that net savings could be made by providing shelter for dairy cattle over much of Australia. Jones and Hennessy (2000) conducted a risk assessment of heat stress on dairy cattle in the Hunter Valley, NSW, which farmers could use in conjunction with a cost-benefit analysis for their own situation. Their provisional cost-benefit analysis, using the method of Davison et al. (1996) demonstrated that the capital costs of $30 per cow to install shade and sprinklers, in order to adapt to increased heat and humidity, resulted in a gross return of $14 per cow. While this analysis didn’t take all factors into account it did suggest that heat stress management in the upper Hunter Valley was cost effective.

Knowledge Gaps and Priorities

- The two most significant high level priorities are to conduct a comprehensive policy analysis and review across agricultural, energy, taxation and trade portfolios (Howden et al. 2007) and to conduct systems analysis of adaptation options across the intensive livestock and other agricultural sectors. Policy analysis is necessary to reduce the risks of maladaptation or counter-acting policy and regulation inherent in portfolios with different objectives. Systems analysis of adaptation options is also necessary to avoid maladaptation that may occur when cross-scale processes or feedback loops are not considered by the farmer or industry participant. Participatory systems analysis, as initiated by Dairy Australia, provides the opportunity for industry participants and scientists to be involved in identifying potential adaptation options and testing their efficacy and practicality.
- Guidelines should be developed for building or retrofitting energy and water efficient livestock production buildings, incorporating options for energy generation and passive or environmental air conditioning. These options may also be built into planning codes and building regulations for future sustainable developments.
- Communication with the industries in terms of the need to take into account climate change in the design of new infrastructure to allow for increased capacity to keep animals cool but also to reduce greenhouse gas emissions in both the construction and maintenance phases.
- Understanding the risks to feed supplies due to reduced or more variable grain yields and/or increased competition from use of feed stock for biofuels or international food markets.
- Assessing the vulnerability of the irrigated dairy industry to prospective reductions in irrigation supply, and placing this within a regional assessment framework.

Table 10.1: Summary of climate change adaptation options for the intensive livestock industry indicating whether the option 1) has already been assessed or is a remaining knowledge gap, 2) is highly feasible, 3) would be feasible / effective immediately, or 4) should be a high priority for research, assessment and implementation in developing adaptation strategies.

Adaptation options	Options already assessed	Options with high feasibility	Immediacy	Priority activities
Policy level				
Comprehensive policy analysis and review across agriculture, energy, taxation and trade portfolios	X	✓	✓	✓
Conduct systems analysis of policy and management adaptation options	X	✓	✓	✓
Building code requirement for passive cooling, appropriate insulation of, and stormwater harvesting from, production sheds	X	✓	X	✓
Zoning for agricultural industrial parks	X	✓	X	X
Understanding the risks to feed supplies from variable supply or competition	X	✓	✓	✓
Assessing the vulnerability of irrigated dairy to reduced water supply	X	✓	✓	✓
Farm management				
Increasing landscape robustness and resilience through revegetation and wetland creation	X	✓	✓	✓
Summer housing for dairy cattle	X	✓	X	X
Matching stocking rates with pasture production	✓	✓	✓	✓
Rotational grazing	✓	✓	✓	✓
Modification of grazing times	X	✓	✓	✓
Night feeding in feedlots	X	✓	✓	✓
Timing of reproduction	✓	✓	✓	✓
Alteration of animal or forage types	X	✓	✓	✓
Ensuring adequate storage of water	✓	✓	✓	✓
Use of supplementary feeds	✓	✓	✓	✓
Redesign of buildings for passive cooling	X	✓	✓	✓
On-site power generation	X	✓	X	✓
Climate information and use				
Improve dynamic climate modelling tailored towards decision making in agriculture	✓	✓	✓	✓
Incorporate seasonal forecasts and climate change	X	✓	✓	✓

Adaptation options	Options already assessed	Options with high feasibility	Immediacy	Priority activities
into farm enterprise plans so as to be able to readily adapt				
Warnings of heat stress days	✓	✓	✓	✓
Water resource issues				
Rehydrating landscapes through wetland re-creation	X	✓	✓	✓
Further improvements in water distribution systems, irrigation practices such as water application methods, irrigation scheduling and moisture monitoring to increase efficiency of use	✓	✓	✓	✓
Develop water trading system (and associated information base) that can help buffer increased variability	X	?	✓	?
Maximise water capture and storage on-farm – needs R&D and policy support	✓	✓	✓	✓

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11: WATER RESOURCES

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Key Messages:

- Three quarters of Australia's irrigated land area has been nominated as occurring in catchments with "high" or "very high" risk scores, highlighting the close spatial and causal links between irrigation and water supply constraints. In the irrigation regions of the Murray-Darling Basin, north-eastern New South Wales and south-eastern Queensland, multiple factors interact to threaten water resources: significant development of surface and groundwater resources, declining rainfall in recent decades, and projected reductions in future rainfall and runoff.
- For adaptation to succeed, a "whole of climate" approach to operational and strategic decision-making is needed. The most prudent course is to treat the decreased levels of rainfall occurring over the past decade as the "new normal". Climate is likely to warm at 0.2°C or more for the next few decades. The greenhouse signal for rainfall over much of Australia is likely to be negative and may accelerate in line with warming.
- On-farm and systems efficiencies can be improved through better use of technology, co-ordination of delivery mechanisms, evaporation control, retrofitting leaky systems, the provision of probabilistic seasonal forecasts and improved scheduling.
- Integrated catchment management is the principal resource management framework in Australia. The relationships between water quality, surface and groundwater extraction, waterway management and land-use need to be considered in an integrated manner, incorporating both climate and non-climatic influences. Institutional arrangements will need to be improved to manage this.
- Assess options for adaptation in highly allocated systems. Existing measures to augment supply or the creation of a free water market may not provide sufficient or socially acceptable solutions if changes to supply become substantial. Additional measures will need to be found, and their social acceptability needs to be considered.
- Develop conceptual frameworks and tools using risk management principles to include climate change in water planning and management. Stakeholders acknowledge the importance of climate change but at present lack methods to include it in their mainstream business. Contingency plans acknowledging progressive levels of stress are needed (e.g., green, yellow, amber and red system status).

Introduction

About 10% or so of national rainfall ends up as runoff, with <1% (15,000 GL annually) estimated to contribute to groundwater (Dunlop et al. 2001b). In 2004–05 an estimated 2.8 million GL of rainfall fell, with a 9% runoff of 242,800 GL (ABS 2006). The 2004–05 water year was relatively dry, following on from a further three dry years including the 2002–03 drought. The amount and proportion would be higher in a wet year. Australia has one of the highest per capita water consumption rates in the world (1.31 ML/person/year; NLWRA 2001). 79,800 gigalitres (GL) of water was extracted from the environment for use in 2004–05 (ABS 2006), up from 72,400 in 2000–01 (ABS 2004). Most of this extracted water was used in-stream, mainly for hydroelectricity generation, so was available for re-use further downstream.

Water consumption was 21,700 GL water in 2000–01 (ABS 2004) but fell to 18,800 GL in 2004–05 (ABS 2006). More than two-thirds (15,000 GL or 69%) of this water was used by the agricultural sector in 2000–01 (ABS 2004) falling to 12,200 (65%) in 2004–05 (ABS 2006). Most of this decline was in agricultural consumption and the one-third or so used for urban and industrial purposes remained fairly constant. This shows the higher security nature of water for urban and industry compared to agriculture. Urban and industrial supply is unlikely to decline significantly until water restrictions have been in place for some time. Under a regime of capped allocations of general and low security water, agriculture is much more exposed to fluctuations in supply.

The accounting of embodied water in goods and services and their trade is an important recent development. The water consumed in the production of a good or service is traced from source to final destination. Lenzen and Foran (2001) showed that 30% of Australia's water requirement was devoted to domestic food production and a further 30% to exports, finding a net annual trade deficit in embodied water of approximately 4,000 GL. This approach allows a triple bottom line assessment of how and where water is used in the Australian economy, and provides the basis for assessing how ongoing socio-economic change may affect water demand (Foran et al. 2005).

Most agricultural purposes require access to an uninterrupted water supply. To achieve this, large infrastructure investments have been made and complex water allocation policies put in place. Between 1857 and 2003 thousands of weirs and locks were constructed (3,600 in the Murray-Darling Basin alone), and thousands of kilometres of levee banks, 446 large dams, and over 50 inter- and intra-basin water transfer schemes (Arthington and Pusey 2003).

This review relies substantially on a recent report *Climate Change and Australian Water Resources: Preliminary Risk Assessment* prepared by CSIRO for the Australian Greenhouse Office and the National Water Commission.

Agricultural Water Use

Agricultural water use includes water for livestock and irrigation. The largest users of water in 2004–05 were dairy farming (2,276 GL or 19%), pasture other than for dairy (1,928 GL), cotton (1,822 GL or 15%), sugar (1,269 GL or 10%) and grain crops (1,162 GL) (ABS 2006). The largest percentage decreases in water consumption from 2000–01 to 2004–05 were for rice (72%) and cotton (37%). This is due to dry conditions experienced mostly in New South Wales and illustrates the opportunistic nature of these cropping systems. Agricultural water uses in 2000–01 and 2004–05 are shown in Figure 11.1.

Slightly more than half the water consumed by the agriculture industry in 2004–05 was self-extracted (6,582 GL or 54%)[1], with distributed water (5,329 GL or 44%) and reuse water (280 GL or 2%) accounting for the remainder. Most the self-extracted water was surface water (74%), while groundwater accounted for 23%. The largest percentage self-extracted surface water was Tasmania (92%), Victoria (84%) and Queensland (76%). Proportions of self-extracted groundwater were: Northern Territory (82%), South Australia (46%), Western Australia (26%), New South Wales (25%) and Queensland (23%).

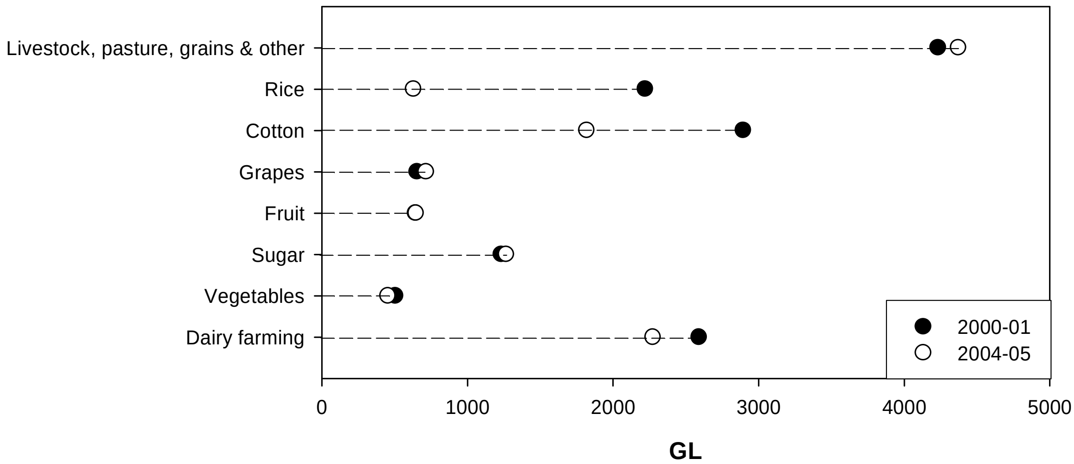


Figure 11.1: Total water use by agricultural activity, 2000–01 and 2004–05 (ABS 2006).

Figure 11.2 shows irrigated crops and pastures as a percentage of total land use in Australia, by drainage division. The majority of intensive crop and pasture irrigation occurs in the Murray-Darling drainage division. New South Wales had the largest irrigation area with 910,000 hectares or 38% of the national total. It is not clear from the National Water Accounts (ABS 2004, 2006), what proportion of water use, especially self-extracted water, is supplied to livestock, compared to the irrigation of crops and pastures.

The area of irrigated land decreased by 8% from 2.6 million hectares in 2000–01 to 2.4 million hectares in 2004–05. Areas irrigated for livestock, sugar, fruit and grapes increased and areas irrigated for dairy farming, vegetables, cotton and rice decreased. Cotton experienced the greatest decrease from 437,378 hectares in 2000–01 to 269,677 hectares in 2004–05. The largest decrease in percentage terms was a 71% decrease in irrigated rice, from 178,965 hectares to 51,216 hectares.

The two states with the largest proportion of high efficiency methods of irrigation are South Australia and Western Australia, both hot, dry states with limited surface water storage capacity. They utilise about one-third drip irrigation compared to a national average of just under 10%. Of the eastern states, Queensland utilises 50% flood irrigation and Victoria and New South Wales use more than 70%.

In terms of reconciling the water accounts with income from agricultural commodities, the gross value of irrigated production does not determine the highest value water use (ABS 2006). The value of agricultural production from irrigation depends on the amount of rainfall and evaporation and non-climatic factors such as land, fertiliser, labour, machinery and other inputs. These factors cannot be separated using current data.

[1] Self-extracted water can consist of surface water (dams, rivers and lakes) or groundwater, but is extracted by the user and not delivered through a distribution system.

The total gross value of irrigated agricultural production in 2004–05 was $9,076 million compared to $9,618 million in 2000–01. The decrease in gross value of irrigated production mainly occurred in New South Wales and Australian Capital Territory combined, from $2,371 million in 2000–01 to $1,867 million in 2004–05. Reductions in income for cotton were $1,222 million to $908 million and rice, $350 million to $102 million.

Irrigated production contributed 23% to the total gross value of agricultural commodities produced in 2004–05. Fruit was the largest contributor to the value ($1,777 million or 20%), followed by vegetables ($1,761 million or 20%) and dairy farming ($1,632 million or 18%).

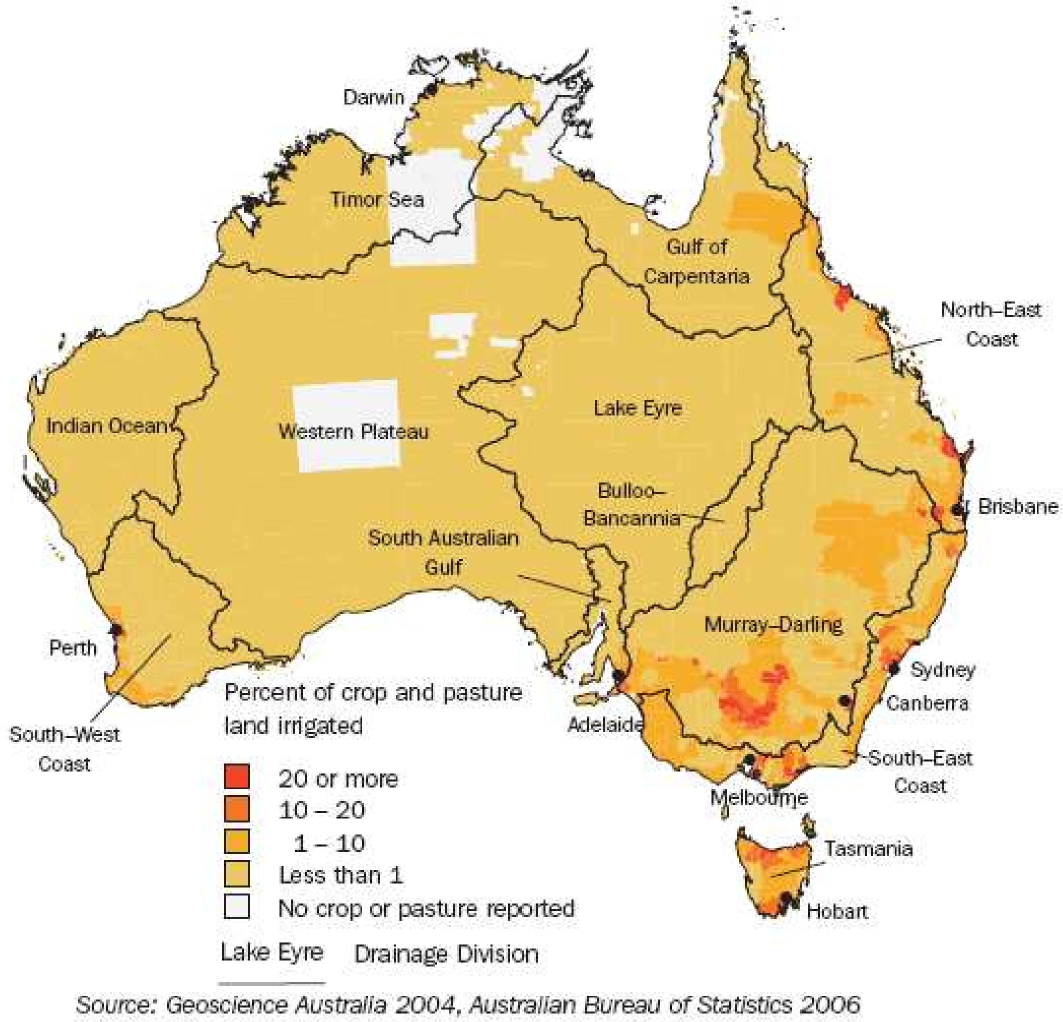


Figure 11.2: Irrigation areas in Australia (ABS 2006).

Establishing Baselines and Planning Horizons

The management of water resources requires a whole-of-climate approach that incorporates ongoing natural climate variability. However, to assay change, a baseline or reference is needed. Climate baselines may include climate trends and different modes of variability. Comprehensive baselines of the total resource may also require its operational and environmental history and responses to past changes.

Baselines:

- Provide a historical record of how climate risks have been managed in the past and of which adaptations were successful and unsuccessful.
- Provide a record of system performance that can serve as the basis for projecting possible future changes.
- Provide a link between past climate and adaptive responses that serve as the building blocks for future adaptation.
- Provide a record of how climate risks interact with other processes such as other biophysical changes, socio-economic change and system performance.

Management decisions are influenced by a range of planning horizons. Some decisions can be ongoing, but others need to be made well in advance. For example, the planning cycle for new supply infrastructure needs decisions on investment, design, environmental impact, public consultation and construction years in advance of when it is required to operate. Its design and operation needs to consider changing climatic risks that range from short-term flooding to long-term fluctuations in rainfall and supply. Different agents (e.g., users, operators, or regulators) may be involved in decision-making, depending on the time-horizon of the activity in question. Managing climate risk is therefore a process of identifying the relevant time horizon for a given activity, the responsible agents and planning in sufficient time to accommodate a changing climate (Table 11.1).

Feedback from the water industry suggests that 2020 and 2050 are the most suitable dates for strategic planning under climate change. For example, strategic planning is often looked at in 5-year increments between reviews (e.g., Catchment Management Authority plans). Targets such as 2015 and 2020 for strategic planning are common. For the next few decades, the main drivers will include current climate conditions, socio-economic trends affecting demand patterns and land-use change combined with climate change scenarios and projected population growth.

Climate baselines

Water management has traditionally applied the instrumental climate record with the assumption that climate is stationary[2]. The bulk of Australia's water supply and distribution systems were developed during the latter half of the 20th century, a period of generally favourable rainfall. Security of supply during that period was high, leading many water managers and users to believe that their systems were largely "climate proof". However, climate variability is now recognised as having significant impacts over decadal time scales.

Different modes of natural climate variability can dominate the frequency and magnitude of risks to water resources (Vivès and Jones 2005). The most significant are decadal modes of variability lasting from twenty to more than fifty years that are linked to ocean-atmospheric phenomena such as the Interdecadal Pacific Oscillation (IPO; Power *et al.* 1999). Changes between different modes can be abrupt and are identified by statistical tests that detect rapid changes while ignoring gradual trends. Variables that show distinct decadal modes include heavy daily rainfall, decadal mean rainfall, El Niño-Southern Oscillation (ENSO) behaviour and tropical cyclones.

[2] Most often assumed as a serially independent random walk of climate variability surrounding a mean value. Climate change is often then imposed as a gradual trend on top of this.

Table 11.1: Management and planning activities in the water sector as they relate to climate over different time horizons.

Decision Type	Time Horizon	Relevant Climate Aspects	Activity	Agent
Day to day management (Tactical)	Intraseasonal	Seasonal availability of water, short-term rainfall events, short-term evaporation rates	Delivery of orders and allocations, flow regulation, flood control, maintenance of water quality, irrigation, drainage	Water operators and users at enterprise level (e.g., farmers, engineers)
Seasonal management (Tactical)	Seasonal	Inter-annual rainfall variability, seasonal soil moisture balance	Allocations, seasonal planning, cropping and stock returns, drought control	Water authorities, farmers, regulatory bodies
Mid-term planning (Strategic)	Multi-seasonal (2–15 years)	Frequency of dry & wet years, decadal variability	Policy (e.g., action plans for dryland and irrigation salinity), economic reform, whole farm planning, catchment strategies, Landcare	Catchment managers, legislators, governments, individual farmers, professional and research organisations
Long-term planning (Strategic)	Decades	Decadal variability, climate change	Infrastructure planning, sustainability	Planning bodies, whole of government approach, visionaries

The two most identifiable modes of decadal variability affect 1) interannual rainfall and 2) decadal average rainfall. In the first mode, oscillating El Niño–La Niña dominated phases of ENSO influenced by the IPO affect the frequency and magnitude of floods and droughts. Changes in a cycle lasting roughly 22 years can be observed around 1895, 1923, 1946–8, 1976 and 1999 (Power *et al.*, 1999; Kiem *et al.* 2003; Kiem and Franks 2004; Verdon et al 2004; Power *et al.* 2005). In the second mode, oscillating drought and flood-dominated periods affect mean rainfall and levels of intensity for several decades or more (Warner 1987, Vivès and Jones 2005). Statistically significant changes from drought to flood-dominated modes have been detected in Australian rainfall records in Eastern Australia in 1946–8 and 1972 and from flood to drought-dominated modes in eastern Australia in 1895 and south-west Western Australia in 1946 and 1965–7 (Vivès and Jones 2005; Li *et al.* 2005). Therefore, the first mode is associated with seasonal risks, whereas the second is associated more with stresses that accumulate over time.

When historical climate is separated into statistically distinct modes, then perturbed by a common set of climate change scenarios, the likelihood of risk can be very different depending on which mode is selected as the baseline (Jones and Page 2001). This is relevant with regard to dry periods lasting a decade in southeastern Australia and three decades in southwestern Australia. For example, in southeastern the decrease in streamflow is equivalent to some of the largest reductions derived from climate model projections for 2030–2050. Inflows into the Thomson Dam in Gippsland decreased by almost 35% in the period 1997–2004, compared to 1984–97 (Marsden and Pickering 2006b). This is as severe as the 5th percentile scenario (drier than 95% of other scenarios) projected for 2050 by the Melbourne Water Study (CSIRO and Melbourne Water 2005).

For the Murray Darling Basin, the mean annual rainfall and modelled runoff, averaged over 1895 to 2006 are 457 mm and 27.3 mm respectively. Over the past ten years (1997–2006), mean annual rainfall decreased to 440 mm, about 4 percent lower than the 1895 to 2006 long-term mean. The mean annual runoff averaged over the MDB in the past ten years (1997–2006) is 21.7 mm, about 21 percent lower than the long-term mean. The biggest differences are in the southern half of the MDB, where the 1997 to 2006 runoff is more than 30 percent lower than the long-term mean, and up to 50 percent lower in the southernmost parts (Chiew et al. 2008).

Clearly, the prevailing mode of climate variability is important. If a brief run of dry or wet years is observed, and random variability is assumed as the cause, a return to "normal conditions" would be anticipated in the short-term. Long runs are more difficult to diagnose and may be due to 1) a statistically rare but random series of annual anomalies, 2) a possible change in a natural mode of variability, 3) a climate change, or 4) a combination of 2 and 3. If a natural mode of variability changes, the new conditions would be expected to persist for some decades but not assumed as permanent. Changes due to human-induced climate change would be considered likely to persist over the very long term.

The continuing dry conditions in southern Australia that have now persisted for a decade would suggest that alternatives two or three or a combination of both (where climate variability and climate change are interacting), are most likely (e.g., IOCI 2002). The Water Corporation in Western Australia has already responded to recent decreases in rainfall and surface water supply by altering their working baseline, previously based on data from the mid 1970s, to data recorded from 1997.

Water resource baselines

Reliable data on water budgets incorporating the hydrologic cycle, and water management and use are required for proper planning of water resources. However, until recently, Australia's water budget has been poorly known.

Two phases of National Land and Water Resources Audit (NLWRA 2001) have created the Australian Natural Resources Atlas[3] that maintains all the data collated for the report, including the status of Surface Water Management Areas (SWMAs) and groundwater management units (GMUs). Other data included are catchment statistics on water supply, quality and use at the management area/unit scale, historical streamflow data and spatial data sets of hydroclimatic variables such as potential evaporation.

Budd *et al.* (2004) reviewed the existing audit data against stakeholder requirements and priorities and identified data gaps, consistency, appropriateness and spatial coverage of data. They found that although the audit was the most comprehensive effort to date, a range of improvements could be made. The comprehensive list of improvements and new data needs listed by Budd *et al.* (2004) would also improve climate change risk assessments. In particular, an accurate national water budget that contains temporal and spatial variability, surface and groundwater relationships, and water quality-quantity relationships would be of value. The *National Plan for Water Security* now authorises the Bureau of Meteorology to collect and publish high-quality water information including a National Water

[3] http://audit.ea.gov.au/ANRA/atlas_home.cfm

Account and periodic reports on water resource use and availability. The Bureau will also be empowered to set and implement national standards for water information.

Water accounts are a vital component of baseline data. The Australian Bureau of Statistics maintains the National Water Account (ABS 2004, 2006b), a physical account that consists of supply and use tables, information on water stocks and related issues. The Water Account integrates data from different sources, making it possible to link physical data on water to economic data. The Water Account uses methods proposed in the System of Integrated Environmental and Economic Accounting (UN 2003). The same methods are used by Foran *et al.* (2005) to construct input-output relationships for water in a triple bottom line physical accounting of water applying economic, social and environmental measures. Water accounting methods are reviewed by Lenzen (2004).

Water accounting methods are in their early stages and require a range of further improvements (ABS 2004; Lenzen 2004). In particular, an accurate national water budget delineating different sources, longitudinal records that can link climate and water use over time and removal of systematic errors is needed. Such improvements and further integration of baseline information would greatly improve the existing capacity to carry out assessments under climate change.

Climate Change Impacts

Projected Climate Change

The most recent projections of climate change for Australia (CSIRO and BoM 2007) present a range of potential changes for a wide range of climate variables. These encompass uncertainties associated with different emissions scenarios and climate model sensitivities, as well as differences between models in forecasting regional climate change.

In contrast with an earlier emphasis on changes in mean climate, changing climate variability and extremes are now widely recognised as greatest source of climate-induced stress affecting most systems, including hydrological systems. This process may involve the existing pattern of variability shifting to a new mean climate, creating new extremes, or involve changing patterns of variability; for example, the changing distribution of daily rainfall in most locations toward fewer raindays with higher extreme rainfall events. This requires a whole of climate approach to water resource management, where climate change projections are combined with knowledge of ongoing processes affecting both short and long-term climate variability.

Temperature

The best estimate of annual warming over Australia by 2030 relative to 1990 is about 1.0°C for the mid-range emissions, with warmings of around 0.7–0.9°C in coastal areas and 1–1.2°C inland. The pattern varies little seasonally (Figure 11.3), although warming is less in winter in the south. The range of uncertainty due to differences between models is about 0.6°C to 1.5°C for most of Australia, with the probability of the warming exceeding 1°C by 2030 being moderate for coastal areas, and high for inland regions (Figure 11.3).

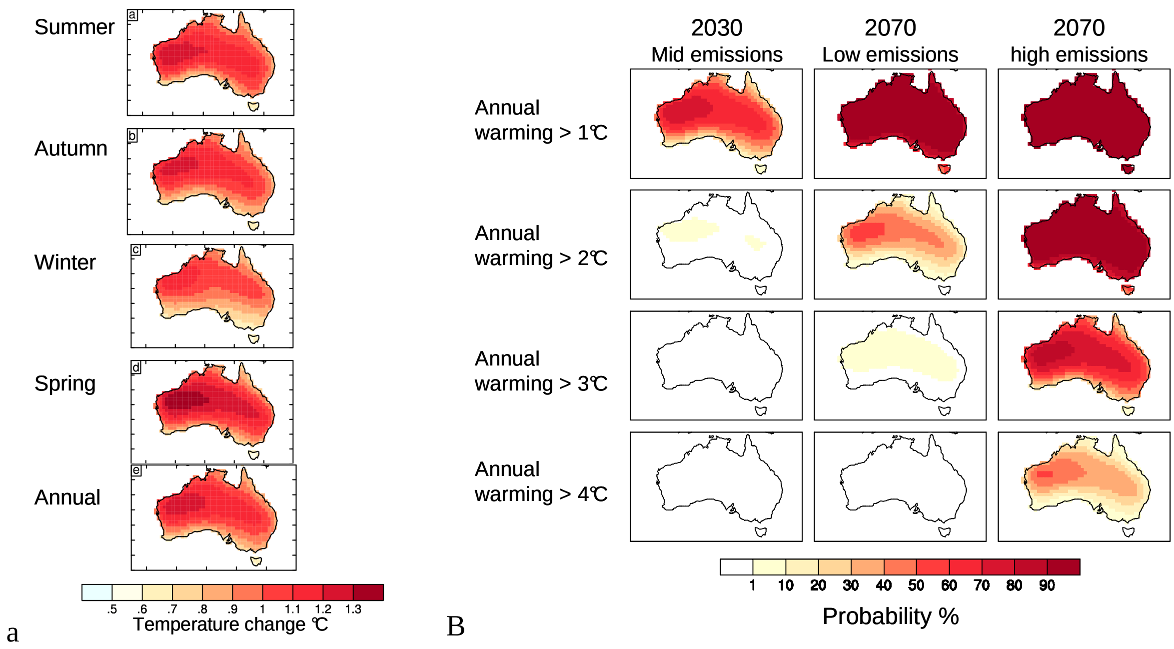


Figure 11.3: a) Best estimate (50th percentiles) of projected mean warming (℃) by 2030 relative to 1990 for mid-range emissions (A1B scenario); b) Probability of exceeding various annual warming thresholds, relative to 1990, based on the spread of climate model results (CSIRO and BoM 2007).

Warming later in the century is more dependent upon the assumed emission scenario. By 2070, the annual warming is around 1.8°C (range of 1.0°C to 2.5°C) for the low emissions case and around 3.4°C (range of 2.2°C to 5.0°C) for the high emissions case. By 2070 for the low emissions case, it is very likely that warming will exceed 1°C throughout Australia, with a 20–60% chance of exceeding 2°C over most inland areas, and about a 10% chance of exceeding 2°C in most coastal areas (Figure 11.3). The high emissions case produces about a 30% chance of exceeding 3°C in southern and eastern coastal areas and a much greater chance inland, while the chance of exceeding 4°C is around 10% in most coastal areas and 20–50% inland.

Substantial increases in the frequency of days over 35°C are likely in most warmer regions. Fewer frosts are also likely.

Rainfall

Climate model results for rainfall change project both decreases and increases for many locations. Where at least two-thirds of the spread of model results is negative, decreasing rainfall is considered ‘likely’. Decreases in rainfall are likely in southern areas in the annual average and in winter, in southern and eastern areas in spring, and along the west coast in autumn (Figure 11.4). Where not deemed likely, model ranges tend towards decrease in most cases. In no region or season do models suggest a likely increase in rainfall.

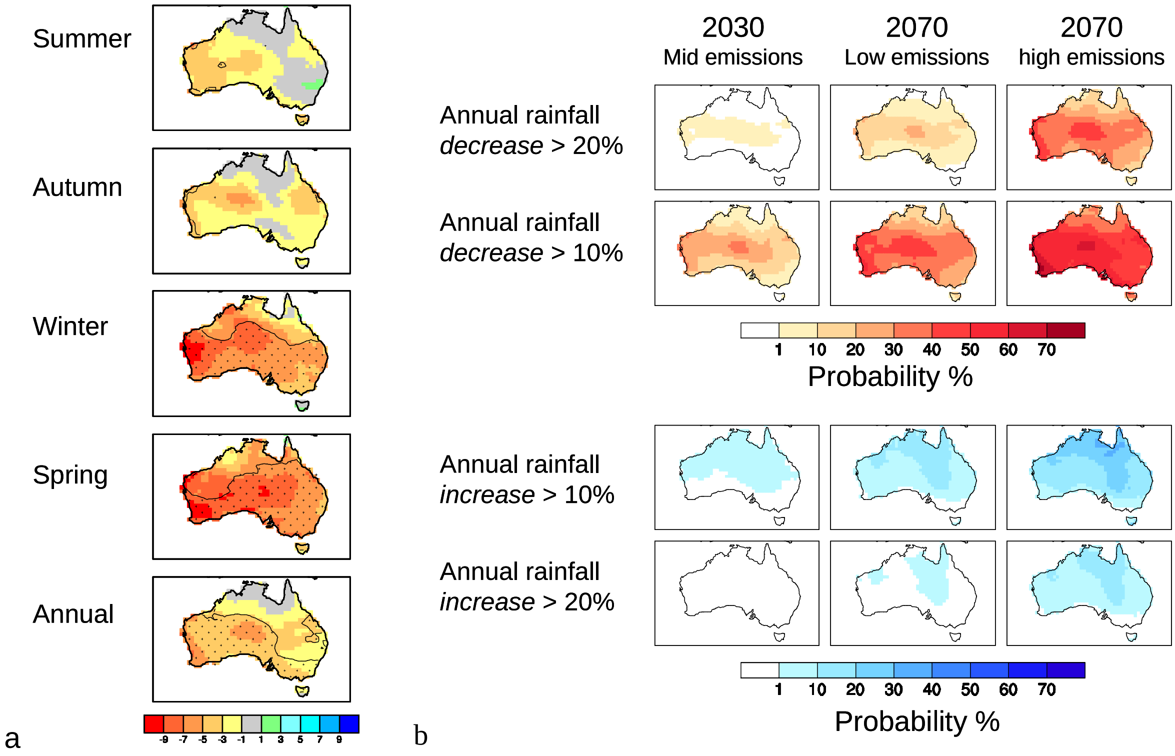


Figure 11.4: a) Best estimate (50th percentiles) of projected rainfall change (%) for 2030 relative to1990 under a mid-range emissions (A1B) scenario. Stippling indicates where a decrease is 'likely' (more than two thirds of the model range less than zero). No areas show 'likely' increase; b) Probability (%) of annual rainfall change, relative to 1990, exceeding various thresholds based on the spread of climate model results. The mid, low and high emissions are A1B, B1 and A1FI (CSIRO and BoM 2007).

For 2030, best estimates of annual rainfall change indicate little change in the far north and decreases of 2% to 5% elsewhere (Figure 11.4). Decreases of around 5% prevail in winter and spring, particularly in the south-west where they reach 7.5%. In summer and autumn, decreases are smaller. There are slight increases in New South Wales in summer.

The range of rainfall change in 2030, allowing for differences between models, is large. Annually averaged, it is around -10% to +7.5% in northern areas and -10% to little change in southern areas. Winter and spring changes range from -10% to little change in southern areas of the south-east of the continent, -15% to little change in the south-west, and -15% to +5% in eastern areas. In summer and autumn, the range is typically -15% to +10%. There is a 20% to 30% chance of a simulated annual rainfall decrease of at least 10% in western and central areas, whereas the probability of a simulated increase of at least 10% is very low (Figure 11.4). Decadal-scale natural variability in rainfall is comparable in magnitude to these projected changes and may therefore mask, or significantly enhance, the greenhouse-induced changes.

In 2070, the low emissions case produces a range of annual rainfall change of -20% to +10% in central, eastern and northern areas, with a best estimate of little change in the far north grading to around -7.5% elsewhere. The range of change in southern areas is from -20% to little change, with a best estimate of around -7.5%. Seasonal changes follow the pattern seen for 2030, but are correspondingly larger. There is a 40% to 50% chance of a simulated annual rainfall decrease of at least 10% in western and central areas, and there is a 10% to 20% chance of rainfall decreases of at least 20% in these areas (Figure 11.4). There is a 10% to 20% chance of rainfall increases of at least 10% in parts of the north.

In 2070, the high emissions produces a range of annual rainfall change in central, eastern and northern areas of -30% to +20%, with a best estimate of little change in the far north grading to around -10% in the south-west. The range of change in southern areas is from -30% to +5%, with a best estimate of around -10%. Seasonal changes may be larger, with projected winter and spring decreases in the south-west of up to 40%. There is a 40% to 50% chance of rainfall decreases of at least 20% in the southwest (Figure 11.4) and a 10% to 20% chance of rainfall increases of at least 20% in the north.

Models also show an increase in daily rainfall intensity (rain per rainy day) and in the number of dry days. Extreme daily rainfall tends to increase in many areas but not in the south in winter and spring when there is a strong decrease in mean rainfall.

Recent analyses of projected climate changes show some consistency with observed changes in regional rainfall in recent decades. For example, decreases in winter and spring rainfall in southern Australia, and increases over Tasmania, are consistent with a strengthening of the westerly frontal system and its movement southward. Recent increases in summer rainfall over north-west and central Australia also resemble projected patterns of change from some climate models, although a recent survey on rainfall trends by Smith (2004) was unable to attribute any definite cause. Recent work suggests the “Asian haze” has generated increasing rainfall and cloudiness since 1950, especially over north-west and central Australia. The effect occurs because the haze cools the Asian continent and nearby oceans, altering the delicate balance of temperature and winds between Asia and Australia (Rotstayn *et al.* 2007).

Interannual rainfall variability over much of Australia, monsoon behaviour and cyclone frequency and distribution are all affected by the El Niño Southern Oscillation (ENSO). The link between rainfall, streamflow and ENSO is statistically significant (Chiew *et al.* 1998). Higher-resolution climate models indicate that under most climate change scenarios inter-annual climate variability is likely to remain high. It is not yet clear, however, whether or not ENSO and ENSO-like conditions will strengthen or weaken. If the nature of ENSO changes, then the predictive modelling systems used to forecast likely supply may need to be recalibrated and new decision-making guidelines developed.

The northern Australian wet season (November–April) is a part of the summer monsoon. Northern Australian monsoon patterns are influenced by events in the Indonesian archipelago and the South China Sea. How these phenomena may change under climate change remains unclear. Although coupled ocean-atmosphere models reproduce many of the phenomena associated with inter-annual variability, long-term changes have low predictability.

Potential evaporation

Changes in temperature and rainfall affect evaporation rates from land (including evapotranspiration from vegetation) and water. Despite rising global temperatures, observations indicate declining pan evaporation in areas of the northern hemisphere over the past 50 years (Peterson *et al.* 1995; Chattopadhyay and Hulme 1997; Thomas 2000). This phenomenon was largely attributed to decreases in solar irradiance and/or changes in the diurnal temperature range and vapour pressure deficit (Roderick and Farquhar 2002). Roderick and Farquhar (2004) analysed pan evaporation data from Australia, concluding pan evaporation has also undergone a marked decrease since 1970. However, more recent assessments following removal of data inhomogeneities suggest negligible positive and negative trends over Australia (Jovanovich *et al.* in press; Kirono and Jones 2007).

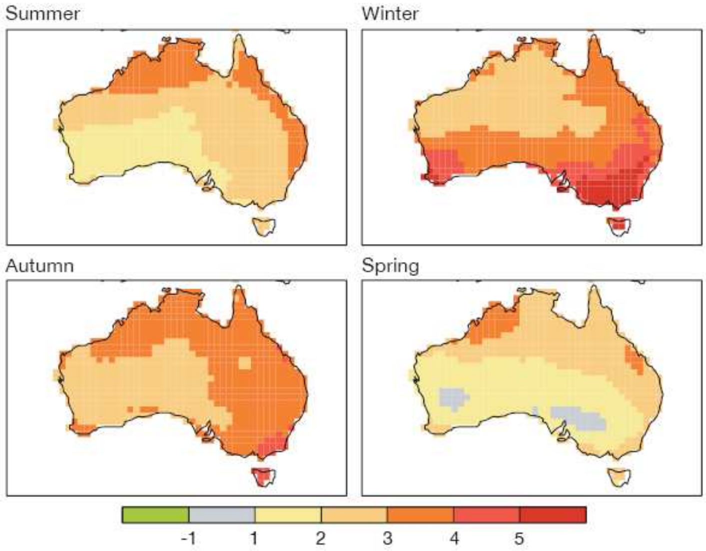


Figure 11.5: Best estimate (50th percentiles) of projected potential evaporation change (%) for 2030 relative to1990 under a mid-range emissions (A1B) scenario (CSIRO and BoM 2007).

Simulated annual potential evapotranspiration increases over Australia (Figure 11.5). Largest increases are in the north and east, where the change by 2030 ranges from little change to a 6% increase, with the best estimate being a 2% increase. By 2070, the B1 scenario gives increases of 0 to 6% (best estimate around 3%) in the south and west and 2% to 8% (best estimate around 6%) in the north and east, while the A1FI scenario gives increases of 2% to 10% (best estimate of around 6%) in the south and west and 6% to 16% (best estimate around 10%) in the north and east.

Extreme rainfall and flooding

Extreme rainfall events have increased throughout most of Australia since the early 20th century (Suppiah and Hennessy 1998). This is consistent with a more vigorous hydrological cycle expected in response to global warming (IPCC 2007). However, these trends have varied significantly. Increases in extreme rainfall of 20 to 30% have occurred in New South Wales in autumn and summer, in the Northern Territory in autumn, and in Western Australia in summer. South-west Western Australia has experienced a 15% decrease in heavy rainfall in winter (Manins *et al.* 2001).

Further increases in the future are projected, although models suggest considerable variation across regions and in the magnitude of the changes (Abbs *et al.* 2005). In northern regions, extreme rainfall events increase in intensity over mountainous terrain but tend to decrease or be weaker elsewhere. Increases in extreme rainfall intensity of more than 70% by 2070 occur in regions that currently experience the most extreme rainfall events. Decreases in extreme rainfall intensity are projected in the lee of mountainous regions. In south-eastern Australia the influence of topography is not as coherent. Small increases occur over the plains of south-western New South Wales with slightly larger increases occurring on the western and northern flanks of the Great Dividing Range. The largest increases in projected extreme rainfall intensity occur along the coastline of southern Victoria and west of Melbourne.

Although a relationship between extreme rainfall and flooding is well established, predicting flood dynamics in response to specific rainfall events remains difficult. Floods range from flash floods from small storm cells through to multi-day events associated with tropical and mid-latitude depressions and cyclones. Flood risks are expected to increase under climate change but these increases will not occur everywhere. Although flood risks could intensify in regions of mean rainfall decrease, increased risks are most likely where mean rainfall remains constant or increases. A significant amount of irrigation occurs on flood plains, but it is unclear how flood risk may change.

Extreme rainfall is often a product of cyclonic activity. Tropical cyclones are responsible for annual damages averaging $267 million, about 25% of all Australian weather-related damages (BTE 2001). Damage stems from extreme winds and flooding associated with heavy rainfall and storm tides. Agricultural infrastructure and crops can both be seriously affected. The central pressure of tropical cyclones over Australia has decreased over the past half century, indicating stronger winds (Pittock 2003), although cyclone numbers have declined. Globally cyclones are expected to strengthen under climate change, both with respect to average wind speeds and associated rainfall (Henderson-Sellers *et al.* 1998; Walsh *et al.* 2004).

Droughts

In Australia, the droughts of 1982–1983, 1991–1995 and 2002–2003 cost $3 billion, $5 billion and $10 billion, respectively (Adams et al., 2002; BoM, 2006). The Commonwealth Department of Agriculture, Fisheries and Forestry is responsible for assessing eligibility for 'drought assistance', based primarily on criteria for 'exceptional circumstances' (AFFA, 2005) and independent advice from the National Rural Advisory Council. Drought assistance includes income support and interest rate subsidies. Exceptional circumstances are declared for "events triggering … an impact so severe and prolonged that they are likely to occur only once every 20–25 years". In the case of drought, the definition of the 1-in-20 year 'event' is not prescribed in terms of rainfall, agricultural yield or farm income – this is assessed by the Department of Agriculture, Fisheries and Forestry.

Droughts can be grouped into four types (AMS 1997):

4. Meteorological drought: A period of months to years when atmospheric conditions result in low rainfall. This can be exacerbated by high temperatures and evaporation, low humidity and desiccating winds.

5. Agricultural drought: Short-term dryness in the surface soil layers (root-zone) at a critical time in the growing season. The start and end may lag that of a meteorological drought, depending on the preceding soil moisture status.

6. Hydrological drought: Prolonged moisture deficits that affect surface or subsurface water supply, thereby reducing streamflow, groundwater, dam and lake levels. This may persist long after a meteorological drought has ended.

7. Socio-economic drought: The effect of elements of the above droughts on supply and demand of economic goods.

A drought index based on rainfall deficiency alone would not account for the effect of projected increases in potential evaporation, so an initial assessment of changes in agricultural drought has been made. There have been no Australia-wide studies of the impact of climate change on hydrological or socio-economic drought.

Agricultural drought is defined as a period of extremely low soil moisture. To compare meteorological and agricultural droughts, the same definitions applied by the BoM to meteorological drought were applied to modelled soil moisture. Three-month periods were analysed to see whether they lie below the first decile (lowest 10% on record). Once a 3-month period was classified as a drought, it remained in the drought category until the deficiency was removed. Drought was considered removed if the soil moisture for the past three months was above the seventh decile (highest 30% on record). Results from two climate models project up to 20% more droughts over most of Australia by 2030 and up to 40% more droughts by 2070 in eastern Australia, with up to 80% more in south-western Australia (Mpelasoka *et al.* in press).

Further work on the three latter forms of drought is needed to provide further information on the risks facing agriculture, particularly as much of the country is currently facing hydrological drought that is unprecedented in the modern era. Continuing events of this magnitude or larger would cause significant hardship.

Surface water supply

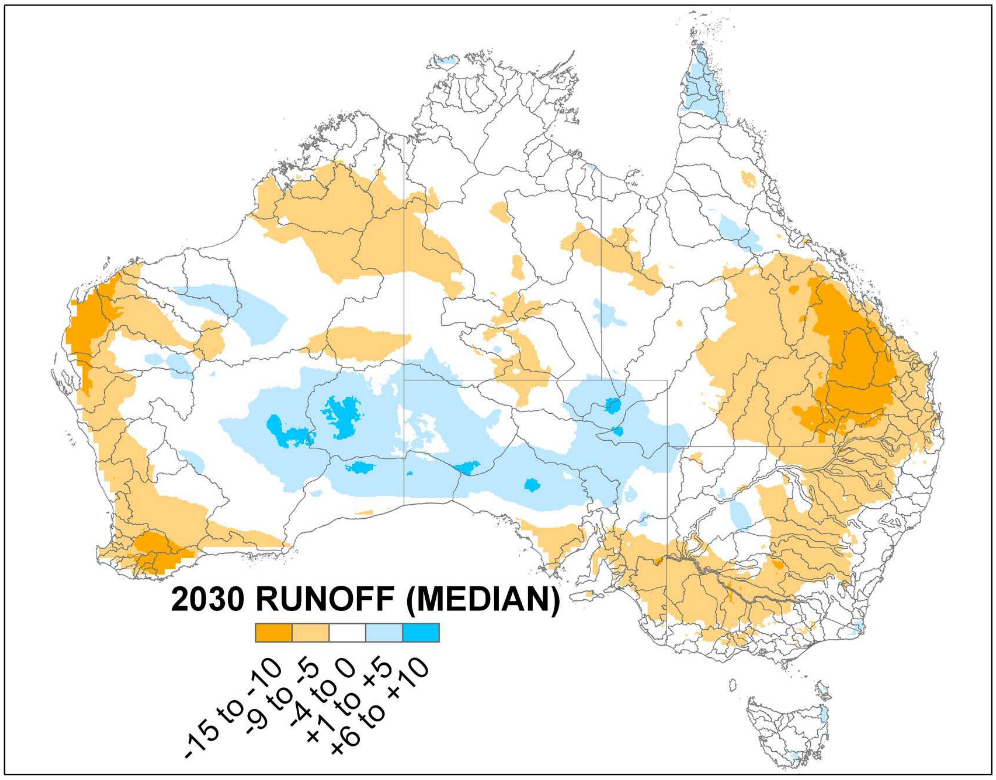
Runoff is a direct measure of climate change's impact on water resources, integrating the combined impacts of changes in rainfall, temperature, and evapotranspiration, but is most sensitive to changing rainfall. Impact assessments and sensitivity studies indicate a general relationship between rainfall and runoff in Australian catchments: a 1% change in mean annual rainfall will result in a 2–3% change in mean annual runoff (Chiew and McMahon 2002; Chiew 2006; Jones *et al.* 2006). The runoff sensitivity to rainfall is greater in drier regions – catchments with low runoff coefficients. Modelling studies also indicate that each 1% increase in potential evaporation will lead to about a 0.5–1% reduction in mean annual runoff (Chiew *et al.* 2005; Jones *et al.* 2006).

Since coupled atmosphere ocean climate models came into use in use in the late 1990s, their results used in impact assessments have projected decreases in streamflow over most of the country. For example, based on output from the UK HadCM2 and HadCM3 models, Arnell and Liu (2001) found marked decreases in runoff over most of mainland Australia with some increases over Tasmania. For the Murray-Darling Basin (MDB), decreases in mean flow ranged from about 12 to 35% by the 2050s, and decreasing magnitude of 10-year maximum and minimum monthly runoff. Recent studies are summarised in Hennessy *et al.* (2007).

Recently the CSIRO 2007 Murray-Darling Basin Sustainable Yields Project estimated the median estimate change in mean annual runoff in the MDB in 2030 relative to 1990 be 5% to 10% lower in the northeast and southern half, and about 15% lower in the southernmost parts. Averaged across the entire MDB, the median estimate is a 9% decrease in mean annual runoff. There is considerable uncertainty in the estimates, and averaged over the entire MDB, the extreme estimates range from a 33% decrease to a 16% increase in mean annual runoff (Chiew et al. 2008).

Natural climate variability is also critical for surface water supply. A probabilistic risk analysis of changes to streamflow in the Macquarie Basin using a range of climate scenarios applied to three modes of baseline decadal rainfall regimes showed that a combination of drought-dominated conditions and climate change produced the worst outcomes (Jones and Page 2001).

A simple but robust model that estimates changes to surface runoff in response to climate change has been developed (Jones and Durack 2005), enabling a broad range of climate futures to be simulated across a range of spatial scales. The model uses rainfall and potential evaporation relationships developed from simulations with hydrological models and can be used where more detailed studies are unavailable. Such estimates are valuable for scoping likely estimates of plausible runoff changes at the catchment scale, and comparing the relative vulnerability of different catchments to climate change.



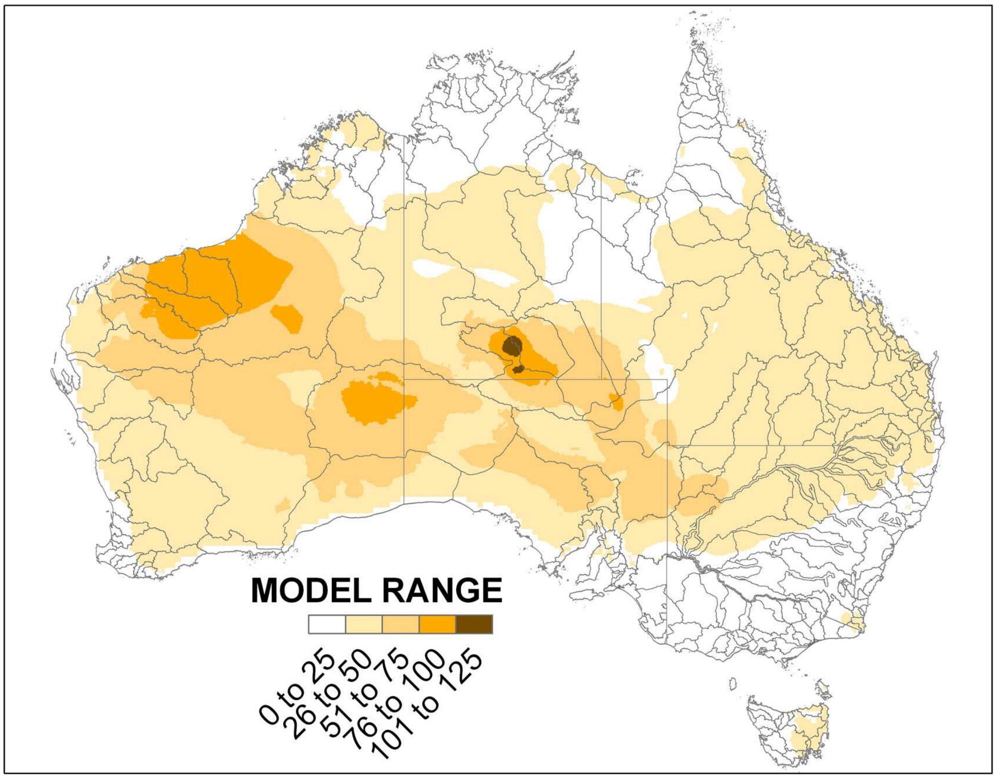


Figure 11.6: Estimated percentage changes in Australian runoff in 2030 produced using a simple hydrological model. Upper) Median estimates based upon a series of 66 simulations using 11 different climate models, three different emissions scenarios, and low and high climate sensitivities. 5th and 95th percentiles calculated from the mean and standard deviations assuming normally distributed data. Lower) Range between minimum and maximum result for all 66 simulations indicating levels of confidence. Smaller ranges indicate higher confidence in the projections. Catchment boundaries correspond to the 325 SWMAs.

A version of this model was applied by Jones et al. (forthcoming) nationally for a rapid assessment of catchment runoff may be altered with climate change under a wide range of plausible scenarios for 2030. These scenarios accounted for a range of climate models, different emissions futures, and different climate sensitivities. Averaged estimates of regional runoff are presented in Figure 11.6a.

Except for some of the arid interior (where there is little effective annual runoff) and the far northern extent of Queensland and the Northern Territory, Australian runoff is projected to decline. Declines are greatest along the west coast, western Victoria/eastern South Australia, and north-east New South Wales to south-eastern Queensland.

The uncertainty of these 2030 estimates is, however, considerable. The 90% confidence limits (the range lying between the 5th and 95th percentiles) produce regional runoff uncertainties of up to ±45% (e.g., central coastal Western Australia). When surveying the results across Australia's 325 surface water management areas (SWMAs), 84% were biased towards runoff reductions, with average changes ranging from 25% to 99% for individual SWMAs. Therefore, most of Australia is exposed to the risk of runoff reductions, and for some catchments, reductions are virtually certain according to the range of models used.

Groundwater supply

Groundwater represented approximately 23% of the water used in agriculture in 2004–05, a slightly larger proportion than 2000–01 due the drier conditions in the later period reducing surface water supplies (ABS 2006). Groundwater use has increased 58% nationally since 1983–4 and by over 200% in New South Wales, Victoria and Western Australia. This volume represents about 10% of the total groundwater that could be extracted sustainably. However, about 30% of groundwater management units are either over- or near fully allocated (NLWRA 2001). Groundwater use is most important in areas with limited surface water supply or surface water supplies need to be supplemented during periods of shortage. Areas where surface water supplies have become fully allocated often undergo a shift towards greater groundwater use. Recently, the interchanges of water between surface water and groundwater and the need to account for this have been better recognised as part of the National Water Initiative.

The volume and sustainability of groundwater relates to the balance between the input of water to a groundwater system (recharge) and the output of water (discharge) and their relation to the total storage volume. The renewability of a groundwater resource depends on the timing and rate of recharge and consequently the age and volume of water. Shallow, unconfined aquifers are usually replenished on an annual basis, but others are recharged by extreme events, sometimes very rare ones. A number of aquifers in inland Australia contain ancient water dating back to wetter periods in the geological past and cannot be considered to be renewable under currently applied planning horizons.

Climate change can affect groundwater balance in a number of ways, with the response often being spatially variable across the same aquifer:

Climate change can affect groundwater recharge by:

- Changing mean annual rainfall. Both diffuse and localised recharge are highly correlated with mean annual rainfall;

- Changing seasonality of rainfall. Summer dominant rainfall occurs at a time of higher evapotranspiration and hence leads to relatively less recharge;
- Changing periodicity of rainfall. For areas where periodicity dominates, any change in the frequency of wetter years or of larger rainfall events will affect the total recharge;
- Changing land use over large areas. The diffuse recharge is strongly related to land use; and
- Changing management of surface water. Localised recharge can be affected by any changes in surface water management.

Climate change can affect the groundwater discharge by:

- Causing shifts in water use between surface water and groundwater;
- Changing water levels leading to changed evapotranspiration;
- Changing water use patterns by vegetation in areas of shallow water tables; and
- Changing surface water management.
- Changes in the balance between groundwater recharge and discharge may impact on the following management issues:
- Groundwater allocation for irrigation and other uses;
- Soil salinity;
- Protection of groundwater-dependent ecosystems;
- Stream depletion caused by groundwater extraction; and
- Deteriorating groundwater quality.

Many of these changes will affect the sustainable yield. For several southern mainland systems, a decrease in winter rainfall is more likely, which would be expected to decrease groundwater recharge and hence, sustainable yield. By 2070, projected decrease in winter rainfall on the south-eastern mainland could exceed 20% and in the south-west 40%. The most optimistic case is either zero or a small increase in rainfall. For inland Queensland and New South Wales, the intake beds for the Great Artesian Basin, rainfall projections tend towards a slight decrease but increases are possible. Increased evaporation, especially over winter and spring in New South Wales and South Australia, may also affect recharge.

Despite a theoretical understanding of the fundamental relationships between surface and groundwater, the level of knowledge regarding the status, sustainable yields, and localised processes needed to quantify recharge and discharge for individual aquifers in Australia remains poor (Neal *et al.* 2001; Crosbie 2007). Improved accounting of groundwater resources is needed to produce a traceable account of groundwater production and use and to provide a reliable baseline for assessing climate change impacts. It is also required for manage interactions between surface and groundwater where both become a common tradeable resource (Budd *et al.* 2004). To aid in this process, significant resources have been allocated by the *The National Plan for Water Security* to more accurate metering and monitoring of both surface and ground water use.

Catchment water supply

In the recent CSIRO report, *The Risk of Climate Change to Australia's Water Resources: a Preliminary Assessment* (Jones et al. forthcoming) the risk posed to water yield from climate change was assessed at the catchment level by calculating a simple qualitative metric, referred to as a *catchment risk score*. It is summarise here. This risk score was constructed using five indicators: status of surface and groundwater resources that represent baseline conditions, recent rainfall and population trends that represent how supply and demand is changing, and projected changes to runoff in 2030. Models of changes to runoff use the simple hydrological sensitivity approach presented earlier.

Data sources for the five indicators are the First National Land and Water Resources Audit (NLWRA, 2001) for surface and groundwater status, the Australian Bureau of Statistics for recent population data, the Bureau of Meteorology for recent rainfall trends and projections of future runoff in 2030 presented in Figure 11.6.

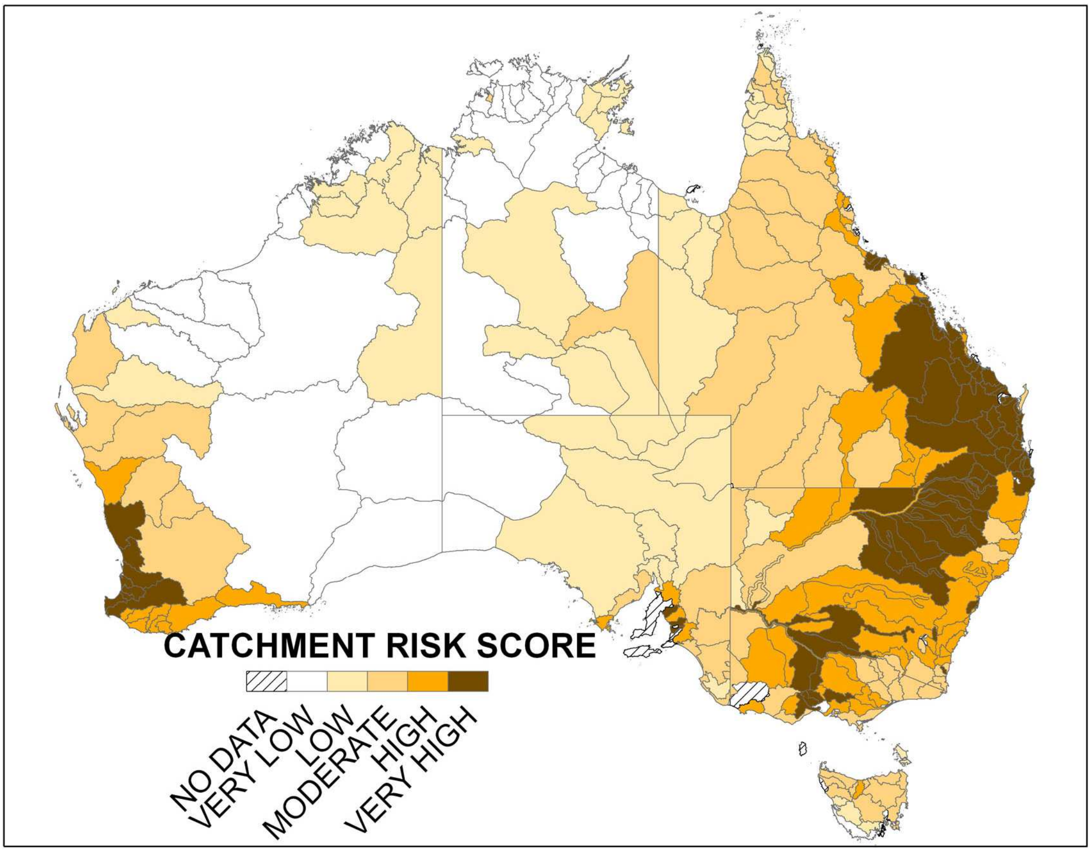


Figure 11.7: Catchment risk scores for Australia's SWMAs based upon various indicators. Catchments at low risk of significant reductions in future runoff and with significant remaining development potential are at a lower vulnerability than those catchments projected to experience significant reductions in runoff and are already fully or over-developed.

Mapping of catchment risk scores illustrates the distribution of water resources risk across Australia (Figure 11.7). "High" to "very high" risks are concentrated in the eastern third of the continent from northern Victoria through to southern Queensland. Across this region, multiple drivers interact to create risk: full to overdevelopment of surface and groundwater resources; declining trends in rainfall over recent decades; population growth; and projected reductions in runoff in 2030. Risk to the catchments of the MDB and south-east Queensland are particularly high. The catchments of south-west Western Australia are also assigned a high risk. There, surface water resources were assigned moderate development status, shallow coastal groundwater resources high development status, and historical rainfall trends and future projections of runoff indicated substantial declines. However, significant potential remains for future development of deep aquifers.

Some less populated areas have relatively high risk scores. For example, depletion of aquifers such as the Great Artesian Basin, combined with declining rainfall and projected reductions in future runoff, will likely affect aquatic ecosystems as well as small regional communities. Most of the areas indicating the lowest risk to supply are regions where runoff increases correspond with limited resource development, such as the arid interior or the far northern regions of the NT and Queensland.

However, this simple risk metric (as well as the methods for deriving the constituent indicators) should be interpreted cautiously due to limitations of the input data and absence of other change criteria. In particular, the risk scores are influenced by the self-assessment conducted by each of the states and territories of sustainable yields of surface and groundwater resources and levels of development, which was provided to the NLWRA (2001). Such assessments are of questionable quality, particularly for groundwater resources. Improvements in the assessment of sustainable yield are needed to provide more reliable estimates of development status.

Uncertainty in future runoff changes is substantial in some regions. Although a best estimate from a range of climate models was utilised, the runoff component should also be treated cautiously. Estimates of projected changes in land use and land cover would help in estimating non-climatic stresses on supply. Although census data are routinely collected, assumptions of potential long-term changes in demand would be improved by the addition of projected population trends to 2030, along with estimated changes in per capita water demand.

Although this risk metric has low precision, it highlights the influence of existing conditions, including the decision-making environment, on future risks. In particular, constraints on water resources in fully to over-allocated catchments and groundwater systems limit resilience and the capacity to adapt to climate change. Such areas have limited flexibility on the supply side of the water balance equation to address growing demand, long-term reductions in rainfall and runoff, or periodic shocks such as droughts. For some regions with the capacity for further resource development, the impacts of climate change on rainfall and runoff, combined with other changes, may be large enough to erode that capacity. In part, this depends on whether climate is changing faster than adaptation to climate-related risks is being planned and implemented.

Agriculture

Dryland agriculture

Aside from the impact of changing rainfall and other variables on various aspects on dryland farming, which are discussed in individual chapters, the most relevant direct impacts on water resources are for stock and domestic water. Stock water supplies can become limited in periods of prolonged drought and water may need to be purchased off-farm and transported to wherever it is needed.

Irrigated agriculture

Almost two-thirds of Australian water consumption in 2004–05 (65%) was used for agriculture, with the great majority being used for irrigation. The irrigation industry is undergoing a period of great change. Climate and the water reform process are two main drivers of that change. Dry conditions across most irrigation regions, combined with caps on supply have combined to create severe shortages decades such changes were anticipated to arise out of climate change.

Few hydrological studies have examined the impact of reductions on irrigation itself. Wang *et al.* (1999) investigated the Campaspe River water supply in Victoria using a scenario of rainfall decrease in the first half of the year and rainfall increase in the second half for a net annual decrease. Irrigation allocations were based on a 'water right' with up to a further 120% of sales water in years when supply was available. The modelled reliability of the basic water right was reduced by 1% in 2030 (0.8°C global warming), 4% in 2070 (1.8°C global warming), and 16% for 4.1°C global warming, the latter temperature plausible late this century. However, under rules applied in the model, irrigation security was maintained at the expense of downstream environmental flows.

Using scenarios derived from the same climate model, a study of the Macquarie River basin in New South Wales estimated inflow reductions into the Burrendong Dam of 10–30% by 2030 with reduced irrigation allocations and environmental flows (Hassall and Associates 1998). An updated assessment using scenarios from a range of models suggested a 'most likely' reduction in inflows of 0–15% by 2030 although the total range was 0 to -30% (Jones and Page 2001; Box 3.1).

Catchment risk scores for Australia's irrigated lands identified 76% of irrigated land area as occurring in catchments with "high" or "very high" risk scores (Figure 11.8), highlighting the close spatial and causal links between irrigation and water supply constraints. In the irrigation regions comprising much of the Murray-Darling Basin, north-eastern New South Wales and south-eastern Queensland, multiple factors interact to threaten water resources: significant development of surface and groundwater resources, declining rainfall in recent decades, and projections of significant reductions in rainfall and runoff in the future.

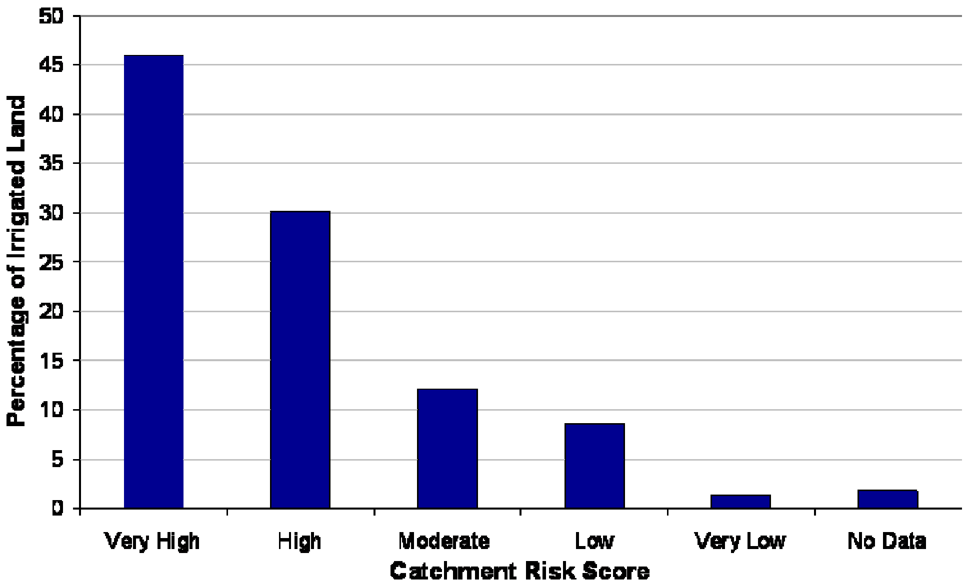


Figure 11.8: Percentage of irrigated land falling within catchments with different risk scores (as defined in section 3.4). Land use data are based upon the 1996–97 1km land use map of Australia produced by the Bureau of Rural Sciences for the National Land and Water Resources Audit.

Although CO_2 can potentially increase plant water use efficiency and growth rates, the extent of this benefit in irrigation systems is poorly known. Hassall and Associates (2002) showed that despite projected reductions for irrigation allocations in the northern rivers of the MDB by 2030, overall increases in cotton production due to higher CO_2 more than compensated for losses in irrigation supply.

To date, no integrated assessments have used crop modelling to assess the combination of irrigation application and CO_2 fertilisation effects, water trading and on-farm and system adaptations to assess how the risk of limited supplies may be ameliorated in future. However, the scientific knowledge required to carry this out does exist.

Where strong interconnections exist between urban, agricultural, and environmental uses, entitlements and allocations for irrigation are likely to decline, as available resources become increasingly constrained, and available entitlements are purchased by other parties. Ultimately these processes are likely to drive careful evaluation of the implications of climate change in determining suitable agricultural areas, raising questions as to whether individual farmers or entire agricultural sectors could gain relief from climate change and other pressures by shifting locations or crop selection.

Water risk may ultimately accelerate structural change in Australian agriculture, favouring large-scale, technologically sophisticated, industrial farming capable of effectively maximising water efficiency and competing in water markets over individual owner operators (Tonts and Black 2002). Such concerns are already present within regional communities. Furthermore, growing pressure on irrigators is likely to drive resistance to water reforms and trading (particularly inter-basin transfers and diversions to urban areas; Tisdell and Ward 2003), and pressure farmers to seek greater water independence through farm dams and bores that, if not managed properly, may compromise the development of robust water allocation systems.

For those possessing an existing water right to irrigate, the challenge of climate change is in coping with potential increases in the frequency or duration of water shortages. With the introduction of supply caps and seasonal allocations (and prices) tied to water availability, it may be difficult for some farmers to acquire sufficient resources during droughts to ensure a successful season. This is especially important for long-lived resources such as livestock and tree and vine crops.

A higher value on water may see farmers enter into water trading, such as price taking in times of shortage, rather than risking crop failure or having to purchase expensive supplies in order to harvest a crop. Therefore, the dynamics of future drought conditions may influence some farm operations. Drought relief is currently based upon the definition of “exceptional circumstances” meaning relatively rare, severe, and unforeseeable drought events (AFFA 2005). What constitutes exceptional circumstances in a changing climate, and what aspects of climate change, if any, may be judged to be foreseeable? We have also seen that baseline conditions can contain different forms of “exceptions”. Whereas many regions of Australia continue to operate assuming recent low rainfall conditions represent “drought”, other areas, such as south-west Western Australia, have redefined what constitutes “normal” conditions.

Some climate change is inevitable – if the level of emissions in 2000 is held constant over time, warming by 2100 is estimated to be in the range 0.9–2.1°C (Wigley 2005). Since 1980, mean global warming has increased by 0.2°C per decade, suggesting that by 2100, a minimum 2°C warming can be expected. Therefore, by the end of the century changes to surface water balance due to human induced climate change are projected to be at least 2–3 times the magnitude of temperature change shown in Figure 11.3.

Adaptation Options

Current Options for Dealing with Climate Variability

As stated earlier, a whole of climate approach is required to deal with irrigation, which is currently undergoing a period of significant restructuring as part of the National Water Initiative (*Young et al*. 2006). Much of the irrigation system and its operating rules were set up during the latter half of the 20th century, a period of generally favourable rainfall. The distributed irrigation system was well-adapted to interannual variability, with large carry-over storages and extensive distribution systems with defined water rights. Self extraction from rivers and streams downstream from those storages also benefited. However, the managed system was operated very conservatively, with allocations often set according to the drought of record, or similar criteria (Long and McMahon 1996). Australian water supply systems were very successful in providing a secure water supply, leading many water managers and users to believe that their systems were largely "climate proof" except for the most severe floods and droughts.

Although managing for these issues will also improve the ability of farmers to respond to climate variability, the industry as it was structured was always going to struggle if water resources were to become scarce. The increasing water consumption that continued until the cap was set in 1996–97, was driving the system towards scarcity, independently of climatic influences.

While many of the current options for dealing with climate variability will continue to be relevant, especially at the individual farm level, at a system level, large changes are already in train. Because allocations were not capped until the late 1990s, specific management for climate variability was secondary to concerns such as managing waterlogging, salinity, efficiency and productivity. These give rise to actions such as the following:

- identifying irrigation seepage hotspots,
- identifying realisable irrigation water savings, through on farm water management and water saving technology,
- improving irrigation scheduling using moisture sensing and better targeting of growth cycles,
- developing national effluent irrigated plantation guidelines, and
- developing farming systems with reduced deep drainage losses.

Rather than separating options for dealing with current climate variability from those aiming to deal with climate change it makes more sense to combine these in a whole of climate approach to adaptation. Changes occurring over the past decade show that climate change (a combination of natural and human-induced) is happening now.

Adaptation Options for Dealing with Climate Change

The following areas are grouped according to process. Increasing irrigation efficiency and seasonal prediction systems are stand alone actions will benefit individual operators and can also be applied at the system scale. They are the subject of a significant research effort. The planning of irrigation futures brings together a large number of strategic and long-term concerns, and provides the platform for their integration. Each element will have an attached set of adaptation options, but these are combined and implemented through the planning process. Finally, the recommended approach used in assessing and managing change is risk assessment and management, in a process that involves stakeholders and researchers.

Increasing irrigation efficiency

Current inefficiencies are estimated as follows (CSIRO 2007):

- Between 10–30% of the water diverted from rivers into irrigation systems is lost before it reaches the farm gate.
- Up to 20% of water delivered to the farm gate may be lost in distribution channels on-farm and around 60% of water used for irrigation on farms is applied using flood irrigation or aerial sprays.
- More than 10–15% of water applied to crops is lost through over-watering, whereas scheduling tools and observational data could more precisely match water application to crop water requirements.
- Inaccurate measurement of water diversions from rivers and water use on farms is leading to unintentional and intentional over use.

Adaptations include:

- Identifying high seepage areas in the delivery system, improving channel efficiency and evaporation controls.
- Efficient on-farm delivery systems, laser-layout gravity systems, replacement with hose, microspray and trickle/drip systems.
- Scheduling according to soil moisture, evaporation measurements, timers and sensors, growth phase of crop/pasture, partial root drying (e.g., viticulture).
- More accurate metering, full monitoring of all extractions, staged metering (detecting system losses), improved data collection for physical accounting.

Seasonal Prediction Systems

The base case in distributed and some extractive systems is that initial allocations based on a water right are made prior to every irrigation season based on the existing resources and updated once or twice during the season. With self extractive systems there may be a finite allocation with the potential to be exhausted under various combinations of low supply and high demand. Seasonal predictions of changes in allocations and crop water balance will allow better forward planning for crops and areas planted, scheduling and minimise price risk if there is a need to purchase supplementary water.

Adaptations include:

- ENSO-related indices can be linked to streamflow, which integrates a great deal of potential uncertainty between rainfall and streamflow for an equivalent level of predictability to the relationship between ENSO indices and rainfall (Khan et al. 2004).
- Developing forecast systems based on a combination of medium range weather forecasting and catchment soil moisture which is even closer to streamflow. Both remote sensing and modelling can be used.
- Water distributors providing likelihoods of changes to allocations based on the above systems.

- Seasonal crop modelling of irrigated crops as is now being done in dryland systems, using ongoing information to reduce uncertainty through the season and better target inputs (water, fertiliser etc).

Planning Irrigation Futures

Strategic planning of irrigation futures between stakeholders and research institutions have the potential to provide better security for the industry, improve environmental outcomes, identify and implement change processes with a shared vision and identify further knowledge needs. For example:

- In Western Australia, the South-West water futures project is developing best land and water resource use options for the South-West irrigation district of Western Australia to ensure maximum economic, environmental and social benefits.
- In Queensland, the Great Barrier Reef floodplain renewal project is helping to change floodplain land management to improve water quality and protect the Great Barrier Reef.
- In Northern Australia, the Northern Australia Irrigation Futures project is providing new knowledge, tools and processes to support debate and decision making regarding irrigation in northern Australia.
- The Murrumbidgee catchment, in the Murray-Darling Basin, is providing groundbreaking knowledge, skills and technology to the world’s biggest and most intensive irrigation regions under UNESCO’s global HELP (Hydrology, Environment, Life and Policy) program.

Developing risk management

Risk is defined as a combination of likelihood and consequence of one or more events. The scope of a risk assessment can be as small or as large as is needed and can encompass the outcomes from a single type of event (e.g., flood risk) through to a full integrated regional assessment (e.g., MDB futures over the coming century).

- For adaptation to succeed, a “whole of climate” approach to operational and strategic decision-making is needed. The most prudent course is to treat the decreased levels of rainfall occurring over the past decade as the “new normal”. Climate is likely to warm at 0.2°C or more for the next few decades. The greenhouse signal for rainfall over much of Australia is likely to be negative and may accelerate in line with warming
- Develop risk-based decision-making to adaptation into all levels of operation and planning from tactical to long-term.
- Develop better understanding of integrated catchment management amongst different users. The relationships between water quality, surface and groundwater extraction, waterway management and land-use need to be considered in an integrated way, incorporating both climate and non-climatic influences. Institutional arrangements will need to be developed to manage this.
- Develop contingency based decision-making instead of “one action fits all circumstances”. Business as usual (green), watching brief (yellow), near critical (amber) and emergency management (red) are all codified stages that contain strategic considerations relevant to planning horizons under climate change depending on the proximity to critical outcomes.
- The assessment of outcomes in value-based terms is an integral part of risk management. Improve multiple understandings of water related “values” through research, community-wide discussion

and outreach in an iterative process where multiple propositions are examined in an iterative process.

Risks of Maladaptation

The cross-cutting nature of water and its importance for so many environmental, social and economic outcomes requires an integrated approach. Without integration, there is a significant risk of unintended consequences. The fear of unintended outcomes is one of the reasons that such debates are amongst the most emotionally charged of public debates, and why discussions of water futures are so vital in rural areas. Some of these risks are:

- Many gravity-fed systems are considered to be inefficient in their water use. Their replacement by more energy-intensive but water-efficient systems shifts the risk from water resources to climate change because of higher emissions. Efforts to offset greenhouse gas emissions from new systems may have an opportunity cost if those offsets themselves are a limited resource and could have been used to offset less tractable emissions. Pumping costs from base load coal-powered energy systems, particularly in Victoria, already carries a significant greenhouse penalty.
- More efficient agriculture leading to less waste water production and therefore reduced inflows into streams and wetlands.
- Stranded infrastructure from the trading of water rights out of an area, perhaps hastened by chronic water shortage, can lead to the abandonment of infrastructure linked to activities that are efficient and productive. This can have flow-on effects into local economies.
- Market power being used to control a significant proportion of the water resource when prices are low, disadvantaging smaller operators, with the water perhaps not being used any more efficiently. Profits being made on speculation and trading rather than on productive uses. Both these fears are currently very active in farming communities.
- Limited uptake of new and cutting edge knowledge because of such fears, the risk of failed investment in applying such methods, in preference to the traditional but less efficient methods.
- New irrigation developments may not be as efficient as they should be because of an unwillingness to bear the upfront capital costs and ongoing costs of managing for sound environmental outcomes.

Costs and Benefits

The costs and benefits of many individual adaptation options, such as technological improvements to improve on-farm efficiency, can be assessed through conventional agricultural economics. Further research in this area is being pursued through bodies such the Co-operative Research Centre for Irrigation Futures[4].

Climate change, combined with full cost measures for water being pursued through the National Water Initiative have the potential to change the economics of irrigated agriculture substantially. Any adverse climate change that increases the scarcity of water will increase the value of water within a water market. Yet, as values rise, investments are likely to be driven toward alternatives to competitive trading of surface and groundwater allocations. Increased water recycling, more efficient

[4] http://www.irrigationfutures.org.au/

water appliances and the construction of a desalination plant are all examples of this process. Such investments may act to dampen rising water prices. Ultimately, any increase in the unit value of water will be capped by the value of commodities that can be produced using water supplied by water distribution authorities.

In Australia, all water supply authorities are in the process of moving to full cost pricing that includes the cost of environmental externalities where feasible and practical. Aside from potential changes in the cost of such externalities, which remain highly uncertain, the main price impact of climate change will be on the cost of underutilised, prematurely abandoned or damaged infrastructure. If climate change is expected to result in excess capacity and/or the abandonment of infrastructure before its construction costs can be written off, water utilities may set higher prices to recover that cost. For example, projects currently being implemented to transfer water from one region to another to secure supply may not be robust to climate change impacts. Given sufficient knowledge of the risks of such impacts to future infrastructure performance, a utility may seek to pass that risk on to end users in order to reduce institutional exposure. In practice, however, low confidence in the ability to predict and attribute climate change means that a price regulator may only allow negligible increases to account for potential infrastructure risks. Private (e.g., on-farm) infrastructure may also be at risk if climate stress leads to a water right being sold.

Furthermore, within the broader community, water also holds very strong social and environmental values. Important decisions on the future of water need to take these values into account. Although some work in this area has been undertaken, further research is needed to ensure that these values are fully reflected in the costs and benefits of adaptations affecting the future of water resources.

Knowledge Gaps and Priorities

Ten immediate knowledge needs listed in *Climate Change and Water Resources in Australia: a Preliminary Assessment* are (Jones et al., forthcoming):

- Develop more comprehensive climate change projections specifically suited to water resource applications in Australia, downscaled for use in water resource assessments.
- Develop hydrological models and water planning models that are responsive to climate change. Much hydrological modelling is based on past relationships between rainfall and runoff. Future relationships will be different and we need models that predict these well for all attributes of the hydrologic regime.
- Better understanding of evaporative demand under future climate and its interactions with vegetation. Changing evaporative demand resulting from altered rainfall, temperature, CO2 concentration and humidity and wind is a major driver of change to water demand, water supply and plant growth.
- Predict consequences of climate change on groundwater recharge, discharge and extractive use, including interactions with surface water systems. Groundwater is becoming increasingly significant as a water source yet we have a much poorer understanding of the consequences of climate change for sustainable extraction rates and a much poorer capacity to adapt.
- Understand how to protect and restore aquatic ecosystems. These ecosystems depend on both surface water and groundwater regimes. Concern over ecosystem protection is growing but

quantitative predictive ecology is needed to assess how systems will respond to climate and water regime changes.

- Forecast and manage future water demands. Climate change will be one of the main driving forces of growing demand in both urban and rural water systems. Water systems are managed to match demand with supply so demand predictions are needed, including environmental demand. Methods to manage demand are equally as important.
- Assess options for adaptability to climate change in highly allocated systems. Existing measures of augmentation of supply or creation of a free water market may not provide sufficient or socially acceptable solutions to some of the larger projected changes. Additional measures will need to be found, and their social acceptability needs to be considered.
- Develop conceptual frameworks and tools to include climate change in water planning and management. Stakeholders acknowledge the importance of climate change but at present lack methods to include it in their mainstream business. Few make contingency plans for the future.
- Develop options for increasing flexibility in our water systems. Water trade, multiple use and new infrastructure can significantly increase our adaptability by allowing freer movement of water and greater ability to deal with climate variability.
- Integrate hydrology and climate in The Australian Community Climate Earth-System Simulator. This will fully integrate the interactions between water and climate and lead to more accurate and more efficient predictions of water resource impacts.

Table 11.2: Summary of climate change adaptation options for the water industry indicating whether the option 1) has already been assessed or is a remaining knowledge gap, 2) is highly feasible, 3) would be feasible / effective immediately, or 4) should be a high priority for research, assessment and implementation in developing adaptation strategies.

Adaptation options	Options already assessed	Options with high feasibility	Immediacy	Priority activities
Operational				
More efficient on-farm use of water through improved technology and scheduling	✓	✓	✓	✓
Develop and apply probabilistic forecasts of likely water allocation changes	✓	✓	✓	✓
Use of water management tools (crop models, decision support tools)	✓	✓	✓	✓
Increase crop choice to maximise efficiency and profit	✓	✓	✓	?
Improve distribution system operation and delivery	✓	✓	✓	?
Increased monitoring of the water cycle for accounting purposes	✓	✓	✓	✓
Manage stream and channel flow regimes to minimise losses and maintain environmental values	X	✓	✓	✓
Strategic				
Build climate change into integrated catchment management and relevant strategic policies	X	✓	✓	✓
Develop more equitable sharing of climate risks amongst different uses (irrigation/environment)	X	?	?	✓
Build climate change risks into caps/bulk allocation arrangements	X	?	?	X
Prepare for altered flood risks	X	✓	X	X
Continue to improve water trading to remove perverse incentives and reduce the transfer of risk, especially during drought	X	✓	✓	✓
Control over the building of private water storages (e.g. developed within guidelines, need water right)	✓	X	?	X
Introduce income spreading strategies to manage risk	X	✓	✓	X
Build flexibility into allocation choices between agricultural, environmental, urban and industrial uses	X	✓	✓	✓
Develop full cost provisions of water and water trading, and a robust water trading system	X	✓	✓	✓
Improve understanding of groundwater-surface water-climate interactions	X	✓	X	✓

Adaptation options	Options already assessed	Options with high feasibility	Immediacy	Priority activities
Improve understanding of sustainable yield	X	✓	✓	✓
Long-term planning				
Incorporate climate change into long-term water sharing agreements	✓	✓	✓	✓
Jointly manage climate change and salinity risks	X	✓	✓	✓
Develop groundwater storage options	X	?	X	X
Build adaptation to climate change into new infrastructure	X	✓	✓	✓
Develop understanding of critical thresholds and limits within water collection delivery and use systems	X	✓	✓	✓
Manage catchments and provide strategic design for land-use to maximise water yield and water quality within a framework of long-term sustainability	X	✓	✓	✓
Institutional capacity				
Develop risk-based decision-making into all levels of operation and planning from tactical to long-term	X	✓	✓	✓
Develop better understanding of integrated catchment management amongst different users	X	✓	?	✓
Develop contingency based decision-making instead of “one action fits all circumstances”	X	✓	✓	✓
Improve multiple understandings of water related “values” through research, discussion and outreach to the community	X	✓	✓	X
Develop a “whole of climate” approach to operational and strategic decision-making	X	✓	✓	✓

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12: MARINE FISHERIES AND AQUACULTURE

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Key Messages:

- General ocean warming around Australia and in particular on the east coast, strengthening of the East Australia Current, is predicted to change the distribution of species targeted in wild fisheries, and modify the location of suitable environments for aquaculture species.
- Consideration of changes in distribution may allow fisheries management to facilitate adaptation to climate change.
- Selective breeding of aquaculture species may allow adaptation to warmer conditions, although changes in location may be inevitable for some operations.
- Focused regional studies on the relationship between the climate variables and the species of interest are one way to improve understanding of the potential impacts of climate change.

Introduction

The key variables expected to drive climate change impacts on fisheries and aquaculture are changes in temperature, ocean currents, winds, nutrient supply, rainfall, ocean chemistry and extreme weather conditions. It is very likely that changes in any of these would also significantly change the marine ecosystems (Denman et al. 1996, Cox et al. 2000, Bopp et al. 2001, Boyd & Doney 2002, Sarmiento et al. 2004), and consequently the distribution, growth, recruitment, and catch of exploited marine species, their prey and predators (Hobday et al 2007b).

To give an indication of how the Australian marine environment may change, we use climate change projections from the CSIRO Mk 3.5 climate model (Gordon et al. 2002). Although there are subtle differences between the CSIRO models and other international models, many of the general trends in these fields are similar and we focus on these trends rather the absolute magnitude of the predicted changes. Output from the model of the future key environmental variables for Australia using greenhouse gas emissions scenario IS92a, often referred to as 'business as usual', are shown in Table 12.1 Projections of climate change for the 2030 decade is one temporal scale of interest to many fisheries and aquaculture operators and managers. However, projections for the 2070 decade are also provided as indicators of longer-term changes.

Marine fisheries and aquaculture are important industries in Australia, both economically (gross value over A$2.12 billion in 2005/06) and socially. The Australian Fishing Zone (AFZ) is one of the largest in the world, ranging from Torres Strait in the far north to waters adjacent to continental Antarctica, and from Lord Howe Rise in the east to Christmas Island in the west. The gross value of Australian fisheries production was estimated to be A$2.12 billion in 2005-06 of which about 35% is from the aquaculture industry (ABARE 2007). Rock lobster, prawns, abalone and tuna are the most valuable fisheries, accounting for 55% of Australia's gross value of fisheries production in 2005-06.

Australian fisheries are managed and regulated using a combination of geographic regions, gear types and species groups. As a result there is no single non-overlapping regionalisation. To describe the Australian fisheries and aquaculture sector for this review, we have used a simplified set of geographic regions that may include multiple fishery types (Figure 12.1). Where a fishery type is conveniently treated singly, such as the pelagic fisheries, we have done so. Aquaculture is also treated as a single region, although we distinguish between geographic areas in the review. These areas can be considered as regional production areas, although again, reporting of value and production statistics can be state-based, commonwealth-based, or fishery-based.

Table 12.1: Observed and projected changes in physical and chemical characteristics of Australia's marine realm including the Southern Ocean. The categories match the sub-sections used in each fisheries and aquaculture chapter. The predictions are derived from the CSIRO Mk 3.5, under greenhouse gas emissions scenario IS92a, which is a mid-range scenario. SST = sea surface temperature, MLD = mixed layer depth. Observations of change come from a variety of sources summarised in the text.

Physical variables	**Observed changes**	**Projected changes**	
		2030's	**2070's**
Temperature and solar radiation	SST: Warming recorded Maria Island, Tasmania of approximately of 1.5℃ since 1950s	SST: Warming of 1-2℃ around Australia with the greatest warming off SE Australia (2℃). Solar Radiation: There will generally be increases in incident solar radiation	SST: Warm of 2-3℃, around Australia with the greatest warming off SE Australia (3℃). At a depth of 500 m warming of 0.5-1℃. Solar Radiation: Increase in incident solar radiation between 2 and 7 units W m^{-2}
Winds, ocean currents, MLD & ocean stratification	Little evidence for changes around Australia	Winds: An increase of 0-0.5 ms^{-1} in surface winds Currents: Increased strength of the East Australia Current	Winds: An increase of 0-1 ms^{-1} in surface winds Currents: A general decline in the strength of surface currents of between 0-1.2 ms^{-1} MLD/Stratification: Almost all areas of Australia will have greater stratification and a shallowing of the mixed layer by about 1 m, reducing nutrient inputs from deep waters
Precipitation, extreme events, and terrestrial runoff	Precipitation Long-term declines in some regions, such as south-east Queensland and south-west Western Australia Storms Increases in intense events noted for recent years	Precipitation Average annual decrease of 0 to 5% over most of Australia. Storms Frequency of intense storms expected to increase	Precipitation Continued decrease over most of Australia. Storms Frequency of intense storms expected to increase
Sea level (not including the rise due to ice sheet melting)	20th century rate of sea level rise of 1.7 ± 0.3 mm yr^{-1}	A rise of 0.3-0.5 m is expected around Australia	A rise of 0.6 to 0.74 m, with greater increase on the east compared with west coast
Acidification (pH)	The pH of surface oceans has dropped by 0.1 units since the industrial revolution	A decline in pH by ~0.1 units	A decline in pH by 0.2-0.3 units
Sea Ice	No significant change in Antarctica over the period 1979-2000, in either observations or model.	Sea ice cover predicted to decrease by 10%	Sea ice cover predicted to decrease in winter (25%), and disappear completely in summer (IPCC 4th assessment WG 1 Report)

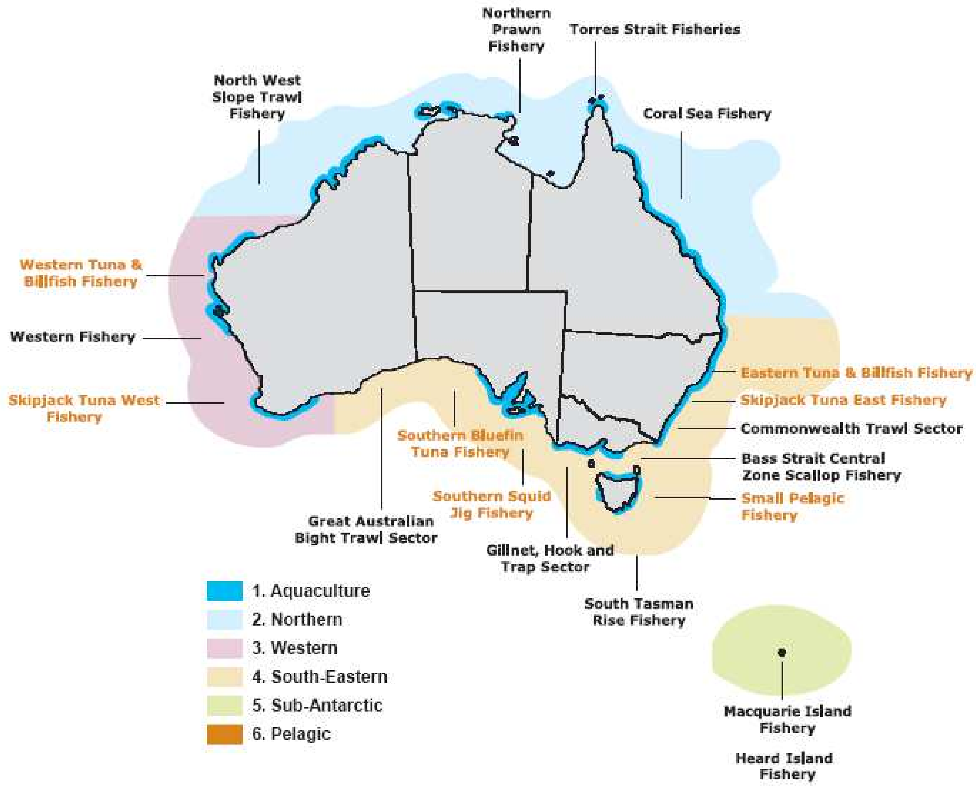

Figure 12.1: Australian fishery and aquaculture regions, together with example fisheries in each region that are covered in this report. These geographic regions have generally coherent changes in the climate system. Aquaculture is widespread around the Australian continent. Pelagic fisheries, denoted by the colour of text, occur in all the wild fishery regions shown in this figure and are treated as a separate section in this review.

Table 12.2: . Aquaculture production (A$'000) of most valuable species per state plus Northern Territory, 2005-06 (from ABARE 2007). * production figures not available, but the species farmed are noted.

Species	NSW	Vic	Qld	WA	SA	Tasmania	NT
Salmon	0	0	0	0	0	221,013	
Trout	1,742	8,624	0	0	447	0	
Tuna	0	0	0	0	155,795	0	
Barramundi	1,238	0	13,900	0	2,029	0	*
Pearl oysters	0	0	0	122,000	0	0	*
Edible oysters	34,093	0	570	0	32,480	16,720	
Prawns	3,387	0	46,500	0	0	0	*

1. **Aquaculture** occurs in most coastal waters around Australia. Salmonids (salmon and trout), southern bluefin tuna, pearl oysters, edible oysters and prawns are the most valuable aquaculture species accounting for 86% of the industry gross value but barramundi and abalone aquaculture industries are expanding rapidly (ABARE 2007). Barramundi, prawns and pearl oysters are grown mainly in Australian tropical and sub-tropical waters while salmon, trout, edible oysters and tuna are cultivated in the cooler southern waters (Table 12.2). The salmon aquaculture industry is based almost entirely in Tasmania.

2. **Northern fisheries** target a wide variety of sea life including penaeid prawns and squid, demersal finfish, shark, grey and spanish mackerel, barramundi, threadfin salmon, Torres Strait lobsters, sea cucumbers, trochus shells, coral trout, red throat emperor, various, live reef fish, and portunid crabs (see Caton & McLoughlin 2005). A broad range of marine organisms is also taken by traditional (aboriginal) hunting, fishing, and gathering, by other artisanal fishing and by recreational fishing (Henry & Lyle 2003). In addition, illegal, unregulated and unreported fishing is growing in northern Australia (DEH 2004). The Northern Prawn Fishery (NPF) is one of Australia's most valuable commercial fisheries (ABARE 2007), averaging 8,500 tonnes of prawn landings per year over the last decade and an estimated 8 to 21 times that amount of bycatch species (Pender et al. 1992, Brewer et al. 1998, Stobutzki et al. 2000). The value of the NPF fishery was A$73 million in 2004-05 (Stobutzki & McLoughlin 2007).

3. Fisheries in the **south-eastern region** comprise an extremely diverse set of activities that can be divided biologically and economically by depth (coastal [0-50 m]), shelf [50-200 m], slope [200-700 m] and deepwater [> 700 m], by gear type/fishery (e.g. southern shark, demersal trawl, scallop dredge, rock lobster, squid), and by management jurisdiction and agency (State-managed fisheries versus those managed by the Australian Government). The region also has the longest European fishery-history in Australia, has the highest numbers of commercial species, and is one of the most heavily exploited regions in Australia. In the 2006 annual report on the state of Australia's fisheries, the Australian Bureau of Rural Sciences (2007) reported that 11 of the 19 nationwide were overfished (Larcombe & McLoughlin 2007). Despite this, the southeast fisheries are still amongst the most valuable in Australia. In 2005/06 the combined value of the Tasmania, Victoria, New South Wales and Australian Government wild fisheries catch in the south-east region (other than pelagic fisheries) was about A$700m: A$240m from molluscs (primarily abalone), A$100m from crustaceans (primarily crayfish) and A$136m from fish (ABARE 2007). The most valuable fisheries - those for molluscs and crustaceans - are mainly inshore and on the shelf. Due to their proximity to major urban centres in south-east Australia, the socio-economic value of the south-east fisheries is substantial.

4. **Western fisheries** harvest demersal, coastal and pelagic species (pelagic species are covered in the pelagic fisheries section). The demersal fisheries dominate with respect to landings and value, and the main species harvested are invertebrates. West coast fisheries (excluding commonwealth fisheries) account for 29% (~A$542 million) of the Australian fisheries production value (ABARE 2007). The relatively high catch of invertebrate species in Western Australia compared to finfish is in sharp contrast to other regions of the world, where finfish production usually dominates (Lenanton et al. 1991, Pearce & Caputi 1994). This low level of finfish production is primarily due to the Leeuwin Current, which brings warm, low-nutrient waters southward along the edge of the continental shelf of the Western Australian coast (Lenanton et al. 1991; Ridgeway and Condie 2004). The western rock lobster fishery is Australia's most valuable single-species fishery. Annual production, which averages in excess of 11,000 t, is worth $250-350 million (ABARE 2007). The other important species include prawns (A$38 million), abalone (A$12 million) and scallops (A$9 million) (ABARE 2007).

5. **Australian sub-Antarctic fisheries**. The Australian sub-Antarctic fisheries concentrate on Patagonian toothfish and mackerel icefish around Heard and MacDonald Islands (3 vessels) and Macquarie Island (1 vessel). The total allowable catch for 2005-06 for Patagonian toothfish and mackerel icefish was 2584 t and 1210 t respectively (Hender and Larcombe 2007). Because of the small number of operators, the value of the catch is not reported in national statistics.

6. The main **pelagic fisheries** in Australia are managed as three separate fisheries, although the target species are the same or similar in all three fisheries. Tuna (yellowfin, bigeye, albacore and southern bluefin) and billfish (broadbill swordfish, striped marlin) are the main target species in the eastern and western longline fisheries (ETBF and WTBF), while southern bluefin tuna is the single target species in a purse-seine fishery in the Great Australia Bight (SBT fishery). A second purse seine fishery for skipjack tuna was recently separated from the ETBF for management purposes, although it remains small in value and tonnage (Larcombe & McLoughlin 2007). The gross value of production in the ETBF in 2005/06 was A$28.7 million, down from A$42.5 million in 2004/05 (ABARE 2007). This decline was due to a decline in the catch of some species e.g. swordfish, lower achieved prices due to a strengthening Australian dollar, as well as a shift to lower value species (albacore). Whether this pattern is related to changes in the regional oceanography is not clear as fishing practices were also altered to target deeper-living albacore. However, the impact of overfishing on swordfish in particular cannot be ignored. Declines in value for the other fisheries were relatively minor 3% (WTBF: 2005-06 A$2.7 million) and 4% (SBT: 2005-06 A$37.5 million, wild caught value), and related to prices for the key species (ABARE 2007).

In the 2006 annual report on the state of Australia’s fisheries, the Australian Bureau of Rural Sciences classified 19 of the 97 stocks assessed as either overfished and/or subject to overfishing, 51 as status uncertain, and 27 as not overfished (Larcombe & McLoughlin 2007). The high proportion of stocks classified as uncertain reflects the addition of new stocks not previously classified and revised classification of some stocks for which assessments were previously thought to be more reliable. The high proportion of uncertainty, especially considering the addition of cumulative pressures associated with a changing climate, highlights the need for reliable assessment information and a growing understanding of complex relationships between fisheries stocks and climate.

7. Climate impacts will also be experienced by marine species of interest to **recreational and indigenous fishers**. Most focus has been for commercial species and fishers, and so the information relevant to other sectors is more limited. Some impacts for the species of interest and the fishers are briefly outlined, based on available knowledge.

The value of fisheries resources to the recreational sector is approximately equal to the commercial sector. Recreational fishers spent nearly $2 billion a year on fishing related activities and equipment, and in the year surveyed by Henry & Lyle (2003), almost 20% of Australians participated in the activity. Significant investment is made by participants, with estimates of over 500,000 boats worth $3.3 billion used for recreational fishing (Henry and Lyle 2003). Approximately 41% of total recreational fishing effort occurs in coastal waters; estuarine waters account for 35%, offshore waters about 4%, while freshwater fishing represents 20% of total effort (Henry and Lyle 2003). The focus of this summary is marine recreational and indigenous fishing.

A number of commercial sectors depend on recreational fishing, including charter boat operators and associated tourism businesses. Approximately 4% (~200,000 in the year 2000) of visitors to Australia participate in fishing activities, with significant spending in some regional economies (Henry and Lyle, 2003).

Indigenous people are a small, but important, proportion of the total Australian population: an indigenous population of about 420,000 people, representing approximately 2.2% of the Australian population, was recognized in the 2001 national census (ABS, 2002). Fishing is a prevalent activity amongst indigenous Australians, with participation rates exceeding 90% reported in northern Australia (Henry & Lyle 2003). Capture of marine resources represents and important contribution to diet and to cultural events in northern Australia.

Target species for both recreational and indigenous fishers differ, and while specific knowledge on many groups is lacking, climate impacts on these species are expected.

Recreational fishers harvest significant numbers of finfish, small baitfish, crabs and lobsters, prawns and yabbies, cephalopods, molluscs and other taxa. The prominent species finfish species in terms of numbers captured are whiting, flathead, Australian herring, bream, King George whiting, mullet, garfish, tailor, Australian salmon and pink snapper (Henry and Lyle, 2003). There is significant overlap between commercial and recreational capture for species, including abalone and rock lobster.

Indigenous fishers harvest millions of aquatic animals in northern Australia, including finfish (particularly mullet, catfish, sea perch/ snappers, bream and barramundi), shellfish, prawns and yabbies, crabs and lobsters, and a range of other taxa. The most prominent non-fish species were mussels, cherabin, other bivalves, prawns, oysters and mud crabs (Henry and Lyle, 2003). Indigenous fishers also harvest some commercial species (trochus, trepang), plus a number of species groups that have protected status for non-indigenous people, including dugong and turtles which have high cultural and spiritual significance to indigenous communities.

Climate Change Impacts

Climate change is generally considered a threat to the sustainability of fisheries and aquaculture in Australia; however, there is little consolidated knowledge of the potential impacts. Opportunities may also result from climate change, however, considerable structural adjustment may be needed to realise these benefits (Hobday et al 2007b). The key variables expected to drive climate change impacts on fisheries and aquaculture are changes in temperature, ocean currents, winds, nutrient supply, rainfall, ocean chemistry and extreme weather conditions. It is very likely that changes in any of these would also significantly change the marine ecosystems (Denman et al. 1996, Cox et al. 2000, Bopp et al. 2001, Boyd & Doney 2002, Sarmiento et al. 2004), and consequently the distribution, growth, recruitment, and catch of exploited marine species, their prey and predators. Given the high endemism of marine species in Australian temperate waters it has been suggested that climate changes would therefore have greater impacts on the biodiversity of Australia's temperate zones than tropical waters (e.g. Pittock 2003; Poloczanska et al 2007b). Nevertheless, many marine species not endemic to Australia are in fact confined to the Indo-West Pacific biodiversity hotspot, with Australia becoming a last refuge for some species affected by degrading environments in neighbouring countries. This is worrying given that several lines of evidence indicate Australia's northern (tropical) ecosystems are vulnerable to climate change (e.g. Hill et al. 2002) in addition to the effects of fishing. Thus, the impact of climate change on these ecosystems may have consequences beyond fisheries (Hobday et al 2007c; Poloczanska et al 2007b).

1. Aquaculture – around Australia

For most marine species growth, survival and abundances of various life stages are sensitive to extreme temperatures and to shifts in temperature regimes. A change of only a few degrees might mean the difference between a successful aquaculture venture and an unsuccessful one. It is expected that climate change will have adverse impacts on the production of species in Australia's cooler southern waters, particularly on Tasmania's valuable salmon aquaculture industry. The largest warming of marine waters in the southern hemisphere is projected in the Tasman Sea, linked to a projected strengthening of the East Australian Current (Ridgway 2007). The stocks of Tasmanian salmon (Atlantic salmon *Salmo salar*) came from Canada and are farmed near the upper limits of their optimal growing temperature in Tasmanian waters. The recent above average summer water temperatures in southern Tasmania have already increased mortality (Pittock 2003) and necessitate remedial action by the industry over the upcoming decade.

Climate change will also influence aquaculture ventures in tropical and subtropical regions (Preston and Poloczanska 2007). Analysis of intensively managed prawn farm ponds Queensland demonstrated variations in pond temperature had pronounced impacts of on farm production, with maximal growth rates of tiger prawns (*Penaeus monodon*) during sustained periods of warmer pond water (Jackson & Wang 1998). This suggests that the production efficiency of tropical and sub-tropical species of farmed prawns, such as *P. monodon* and *P. merguiensis*, might be increased by a rise in water temperature. Rising temperatures may not only enhance growth rates at existing sites, but also extend the cultivation area suitable for farming these species further south. On the other hand, an increase in pond water temperature might threaten the viability of farming cooler-water species, such as the penaeid *P. japonicus*, whose production is restricted to a relatively narrow range of latitudes compared to the sub-tropical species (Preston et al. 2001a). The projected decreases in rainfall over much of Australia will impact freshwater aquaculture industries that rely directly on rainfall to supply their dams or ponds or to recharge groundwater supplies. Adequate supplies of freshwater are required to maintain the water quality in these systems.

The projected increases in the intensity of storms and cyclones will increase flood risk which are a threat to stock through overflows or damage to pond or dam walls. For coastal and offshore aquaculture, more frequent and intense storms result in increased physical damage and stock losses, both of which are costly to operations. Many coastal processes, such as sediment transport, happen mostly during high-energy events (storms). An increase in storm activity may therefore change the direction of river flow, and initiate erosion. These and other effects can affect facilities outside the direct exposure to increased wind and wave activity. For example, in April 1996 Australian southern bluefin tuna farms at Port Lincoln in South Australia suffered losses of up to 75% of total production, which was attributed to asphyxiation of fish by sediments re-suspended during a severe storm (Preston et al. 1997). Any severe flooding event could result in mass mortalities of animals in aquaculture ponds, open-water rafts, and lines or cages in coastal and offshore areas.

2. Northern fisheries region

Notwithstanding regional and species differences in the relationship with rainfall, penaeid prawn fisheries and other estuarine-dependent fisheries throughout northern Australia appear to be somewhat sensitive to climate-related changes in rainfall and freshwater flow (see review by Robins et al. 2005). The sensitivity of northern Australia's penaeid prawns to freshwater flows is also well illustrated by the demonstrated relationships between the southern oscillation index, which is strongly associated with regional rainfall patterns, and both banana prawns (positive) and tiger prawns (negative) (Love 1987, Catchpole & Auliciems 1999).

Changes in rainfall and freshwater flow patterns would also be likely to change nutrient runoff into Northern Australia's coastal waters, which strongly influences the productivity of these otherwise low-nutrient tropical waters (see Vance et al. 2003). Alteration of freshwater flows related to changes in climate patterns might affect northern Australia fisheries in other ways as well. For instance, a loss of synchrony between the timing of life history stages and environmental forces could disrupt reproductive stages of life cycles and community interactions, especially considering that other interacting species will be responding to these environmental changes in different ways. Seagrass beds and mangrove forests are considered critical nursery habitats for many marine species including commercially-targeted prawns (Vance et al. 1990, Loneragan et al. 1994, Haywood et al. 1995, Sheaves 1998, Blaber 2000). For example, catches of tropical commercial species such as banana prawns, mud crabs and barramundi have been shown to be related to mangrove abundance and extent (Lee 2004, Loneragan et al. 2005, Manson et al. 2005). These habitats are particularly vulnerable to cyclones, sea level rise, and their interactive effects. Projected sea level rise is expected to considerably reduce these habitats in the southern Gulf of Carpentaria (Hill et al. 2002), an area critical to much of northern Australia's prawn fisheries while projected increase in cyclone intensity will increase disturbance regimes in northern waters .

3. South-east fisheries region

Warming in the south eastern portion of Australia's ocean is projected to be the greatest in the southern hemisphere (Ridgway 2007). This warming will impacts fished species in a variety of ways, including growth, distribution and abundance (Thresher et al 2007b).

Juvenile growth rates of shallow water, commercially exploited fish species in the southeast have increased significantly since the early 20th century, based on historical analysis of the width of annual increments in their otoliths (Thresher et al. 2007a). The changing growth rates do not appear to reflect changes in the abundance of the fish (due to effects of fishing, for example), but rather correlate significantly with the Maria Island temperature time series (Thresher et al 2007a, b). This increase is restricted to shallow water species; among deeper (>1000 m) species examined, growth rates have been falling, paralleling declining water temperatures at intermediate depths. An effect of water temperature on growth rates is not surprising, as water temperature is one of the principal determinants of growth rates in fishes, as in other poikilothermic species. Consequently, increased growth rates could be widespread among shallow water marine species in southeast Australia. The consequences of such changes on population and community dynamics have not yet been examined.

The projected warming of ocean waters will have profound effects on the distribution of many species. As a result, we can expect to see major changes in community composition and ecosystem function as species geographical distributions shift northwards and phenology alters. Such changes are already being recorded in commercial and non-commercial temperate fish species in the Northern Hemisphere

(Perry et al. 2005, Brodeur et al. 2006) and similar shifts are emerging from the sparse Australian data (Last pers com). Unlike Northern hemisphere scenarios, however, the east-west orientation of the temperate Australian coastline and restricted continental shelf to the south means there are few opportunities for species to move south as water temperatures increase (Poloczanska et al. 2007).

In the last decade, there have been conspicuous changes in the distribution of Tasmanian marine fishes. Some 36 species in 22 families (about 10% of the inshore families of the region) have exhibited major distributional changes: some have become newly established south of Bass Strait; others have markedly increased in abundance in southern Tasmania, by shifting their ranges south along the Tasmania coast; and others are totally new records for Tasmania (P. Last, in Lyne 2005). Most of the species exhibiting a clear poleward shift in distribution are reef species, mainly western warm temperate or eastern warm temperate species. Many are normally found off the NSW coast, in habitats also associated with the long-spined sea urchin, *Centrostephanous rodgersii*. This urchin, an important habitat modifier in New South Wales, crossed Bass Strait in the mid-1960s and was first discovered on the east coast of Tasmania in 1978 (Johnson et al 2005; Ling et al in review). The poleward shift in the distribution of this species has been associated with the decline of urchin barrens on the NSW coast, which adversely affected the local abalone fishery, while its arrival in Bass Strait and subsequent spread along the east coast of Tasmania has led to development of extensive urchin barrens in areas where they did not previous exist. The arrival of *C. rodgersii* off Tasmania appears to be disrupting the existing balance between macroalgae, abalone, rock lobsters and the native urchin, which apparently accounts for a negative relationship between the abundance of *C. rodgersii* and the density of commercially fished abalone and rock lobster. It is predicted that without management intervention, *C. rodgersii* barrens will eventually cover 50% of the rocky reef habitat on Tasmania's east coast and have serious implications for the sustainability of rock lobster and abalone fisheries (Johnson et al. 2005).

The gemfish fishery, already under pressure from apparent over-fishing (like many of the south-east stocks), collapsed altogether when the zonal winds declined to their predicted low point in the 10-year cycle (1989). In fact, the zonal winds in this year were at the lowest levels ever reported. Since then, the winds have fallen further, perhaps reflecting the predicted onset of overall weak zonal winds in the south-east region due to climate change, and also perhaps explaining why, despite the fishery being closed, there has been little or no sign of recovery of the eastern gemfish stock (Caton & McLoughlin 2004). Observations of an increase of juveniles in 2003/04, based on incidental catches, have been interpreted as suggesting improved recruitment (Larcombe & McLoughlin 2007), which would be consistent with an increase in the persistence of the zonal west winds during that period.

4. Western fisheries region

The influence of ocean temperatures along the west coast of Australia is expressed through changes in the Leeuwin Current. The major influence of the Leeuwin Current on recruitment of fished species is during their larval phase (Lenanton et al. 1991, Caputi et al. 1996). The strength of the current has a significant positive influence during the larval stage of the western rock lobster, *Panulirus Cygnus,* but a negative influence on the larval life of the scallop *Amusium balloti* in Shark Bay and at the Abrolhos Islands (Pearce & Capuiti 1994). For pelagic finfish species, the current has an adverse effect on the survival of pilchard larvae (*Sardinops sagax neopilchardus*), but a positive impact on whitebait (*Hyperlophus vittatus*) and also on recruitment of Western Australian salmon (*Arripis truttaceus*) and Australian herring (*Arripis georgianus*) to South Australia (Pearce & Capuiti 1994). The current appears to have a correspondingly negative impact on the recruitment of Australian herring in the south-west of Western Australia.

Western Australian fisheries, such as the rock lobster fishery, also correlate (some positively, some negatively) with phases of the El Niño-Southern Oscillation (ENSO) as well as the strength of the Leeuwin Current through unknown mechanisms (Penn et al. 2005). For example, pearl oyster (*Pinctada maxima*) catch rates are affected by a number of environmental variables including El Niño events: catch rates were enhanced two years after El Niño events (Hart et al. 1999). Explanations for the positive relationship between Leeuwin Current strength and levels of rock lobster settlement have shifted from the direct influence of ocean currents in transporting larvae to the indirect influences on their growth and mortality. The available information suggests two hypotheses. Firstly, laboratory tests indicate that the warmer waters associated with a stronger Leeuwin Current could help the growth and survival of the larvae. Secondly, the south-flowing Leeuwin Current may increase larval retention by eddies and assist in the transport of the late-larval stages and puerulus across the continental shelf into coastal reef nursery areas, especially in the southern areas like Cape Mentelle (Caputi et al. 2001, 2003). The fluctuation in value of the rock lobster catch, which is related to environmental variation indicates that socio-economic effects can be large. Under various climate-change scenarios, changes in the frequency of El Niño and the strength of the Leeuwin Current may directly impact the rock lobster fishery. It is not known whether the species' spawning strategy would adapt to a sustained shift to a weaker Leeuwin Current and warmer temperatures. Further, it is unclear whether these mechanisms would continue to operate under the combined influence of a sustained weaker Leeuwin Current (which would tend to reduce temperatures) and the regional rise in sea-surface temperature along the coast of Western Australia due to global warming. A major concern is that climate change might cause a systematic shift in the larval settlement–Leeuwin Current relationship, which could invalidate the present management approach. The combination of ocean warming and changes in the strength of the Leeuwin Current might increase the growth rate of larvae, changing their time of settlement (Matear et al 2007).

5. Sub-Antarctic fisheries region

Antarctic fish are adapted to stable water temperatures within narrow ranges (Roessig et al. 2004). Evidence suggests life stages of Antarctic fish may be particularly sensitive to changing temperatures mediating population response (Hill et al. 2005). As temperatures rise, Antarctic fish will disappear from banks and around oceanic islands at the northern edges of their distributions, such as the mackerel icefish from banks north of Heard Island (Kock & Everson 2003). Low stock sizes of mackerel icefish around the Kerguelen Islands since the mid-1990s may have been partly caused by poor recruitment and/or increased emigration due to warmer than average water temperatures (Kock & Everson 2003). Even slight changes in the temperature of Antarctic waters may cause Antarctic fish to shift migratory patterns and distributional ranges (Roessig et al. 2004). On a positive note, the warming of the ocean and the infusion of freshwater are likely to intensify biological activity and increase growth rates of fish (Everett & Fitzharris 1998). Ultimately, this is expected to lead to an increase in the catch of marketable fish and in the food reserve, which could offset the long-term nutrient loss resulting from reduced deep-water exchange.

The impacts of ocean acidification on Southern Ocean krill, fish and other species has not been assessed. Given the projected under-saturation with regard to calcium carbonate of the entire Southern Ocean water column by the end of this century (Caldeira & Wickett 2005, Orr et al. 2005), this must be a priority area for research. As well as dissolution of carbonate (aragonite and calcite) shells and structures produced by calcifying organisms (Riebesell et al. 2000), acidification will increase physiological stress on marine fauna by influencing metabolic rates (Pörtner et al. 2004). The impacts of ocean acidification are most likely to be evidenced in alteration of plankton communities at the base of food webs, such as pteropods, with their aragonite shells (Orr et al 2005). Pteropods are prominent components of the Southern Ocean web and also account for the majority of the annual export flux of both carbonate and organic carbon in the Southern Ocean. Populations are likely to decline in the Southern Ocean over the coming century as the under-saturation with regard to calcium carbonate of Southern Ocean waters increases, with knock-on effects for higher trophic levels such as commercial fish and baleen whales. Climate change in Antarctica is also projected to reduce the areal extent of sea-ice; this would almost certainly reduce photosynthetic carbon fixation, destroy habitats, and disrupt the life cycles of many marine animals including commercial fish (Poloczanska et al 2007a).

6. Pelagic fisheries region

Ocean temperatures have a demonstrated effect on the distribution of the target species in Australia's pelagic fisheries (e.g. SBT: Reddy et al. 1995). Evidence is also strong in other parts of the world, and temperature is one of the strongest drivers of pelagic fish distribution (Laurs et al. 1984, Andrade & Garcia 1999, Schick et al. 2004, Kitagawa et al. 2006). The strongest environmental signal in the ocean, the ENSO phenomena, has been shown to have a major impact on the distribution of tropical tunas (Lehodey et al. 1997).

On the east coast, pelagic species are captured in the Coral Sea, East Australian Current, and Tasman Sea regions. There are seasonal changes in the abundance of species such as yellowfin (*Thunnus albacares*) and bigeye tuna (*T. obesus*) captured in the longline fishery that are positively linked to the expansion and contraction of the East Australian Current (Campbell 1999). At a finer scale the distribution of yellowfin tuna has been linked to the distribution of mesoscale environmental features such as eddies generated by the East Australian Current (Young et al. 2001). The known relationships between the distribution and abundance patterns of some pelagic species on the east coast suggest that changes in the strength of the East Australian Current would have dramatic effects on the availability of key pelagic species to the fishery, although the mobility of the fishing fleets might reduce the immediate economic impact. Changes in productivity can also affect the pelagic ecosystem and the harvested species at the top of the food chain; research in this area is in its infancy (Young & Hobday 2004). Preliminary analyses have found spatial differences in productivity and pelagic ecosystem structure, and it is believed these regional differences could mimic the temporal changes that might occur as a result of climate change.

In southern Australia, juvenile southern bluefin tuna (SBT) have been the subject of several studies investigating distribution and abundance relationships to mesoscale environmental variability (Hobday 2001, Cowling et al. 2003) or to prey (Young et al. 1996). In general, the environmental linkages to abundance are not strong at the mesoscale, although problems with the spatial resolution of some biological data have confounded analyses. A recent study did not find a link between an apparent decline in a fishery-independent abundance index of age-1 SBT and environmental conditions (SST, Leeuwin Current strength, winds) in south-western Australia (Hobday et al. 2004). This index of abundance has not yet been validated, and so environment-SBT relationships may have been overlooked. In contrast, at a larger scale, seasonal changes in the abundance of juvenile SBT (ages 1-5) in southern Australia are well documented. SBT are resident along the shelf during the austral summer (Cowling et al. 2003) and then migrate south during the winter. Interannual variation in SBT abundance within the main fishing grounds in the Great Australia Bight has not been linked to the environment, although variation in the arrival time of schools has been attributed to unspecified environmental factors (Cowling et al. 2003). Variation in the availability of SBT prey (sardines and anchovies) as a result of changes in wind-driven upwelling (Dimmlich et al. 2004) are also likely if climate change affects the strength of upwelling favourable winds (Hertzfeld & Tomczak 1997), which might ultimately affect the pelagic predators. Finally, the impact of climate change on the winter SBT feeding grounds in the southern ocean may be more dramatic (e.g. Sarmiento et al. 2004); it remains an area for investigation (Hobday pers. comm.).

The two pelagic longline fisheries have a large number of byproduct and bycatch species, which may also experience climate-related impacts, while two lower value fisheries (squid and small pelagic fisheries) target key species at intermediate trophic levels. These intermediate levels contain crucial species for the rest of the ecosystem and could be particularly sensitive to climate impacts (e.g. Cury et al. 2000, Rose 2005, Hunt & McKinnell 2006).

Pelagic squid captured in the southern squid jig fishery (SSJF) have more flexible life history strategies and greater tolerances to environmental change than the fishes making up the small pelagic fishery (SPF) (Pecl & Jackson 2005). They could benefit from climate induced changes in the regional oceanography, possibly at the expense of the species of the SPF which feed mainly on zooplankton that are restricted to temperate waters (Young et al. 1993). In the Eastern Tropical Pacific Ocean, there has been an expansion in the range and increase in abundance of the jumbo squid, Dosidicus gigas. The jumbo squid expansion has been linked to the collapse of the shortbelly rockfish *Sebastes jordani*, which is also a prey of the squid (Field & Baltz 2007). Although the cause of the increase in these squid is unclear, warming of the regional oceanography has been implicated (Olson & Young 2007).

In the east coast small pelagic fishery (since ~1985), changes in fishing method (purse-seine to midwater trawl) have confounded potential environmental relationships with small pelagic fish distribution and abundance (Lyle et al. 2000) that have been so clearly documented elsewhere in the world (e.g. Chavez et al. 2003, Jacobson et al. 2001). However, off the coast of Tasmania, declining growth rates of jack mackerel and a change in the age structure of the catch through the 1990s may have both an environmental and an anthropogenic component (Lyle et al. 2000, Browne 2005). Changes in the relative dominance of the East Australian Current and the sub-Antarctic water masses, and consequently the regional prey communities have also been implicated in changes in local productivity off the east coast of Tasmania (Young et al. 1993, 1996). For example, the disappearance of krill, *Nyctiphanes australis*, from the shelf ecosystem of eastern Tasmania during a warm (La Nina) event in 1989 was linked to the simultaneous disappearance of their main predator, jack mackerel (*Trachurus declivis)* (Young et al. 1993). Given that *N. australis* is at the base of most Tasmanian shelf marine ecosystems, and that it is a cool-water species, any persistent warming of the regional oceanography would have a profound effect on krill-dependent food chains. These food chains include cephalopods (Pecl & Jackson 2005), seabirds (Bunce 2004), small pelagic fish and tunas (Young et al. 2001).

7. Recreational and Indigenous fishers

Some impacts of climate change will be similar for recreational, indigenous and commercial fisheries, including:

- Movement of target and bait species to more southern latitudes or to greater water depth, related to ocean warming. This may result in an increase in tropical species for south-eastern Australia in particular.
- Changes in availability, due to changes in local abundance and/or growth rates that may interact to reduce catch where size limits are employed. Species reliant on freshwater flows (estuarine) may be particularly impacted by terrestrial and marine impacts.

Environmental changes may impact both recreational and indigenous fishers more severely than commercial fishers who generally use larger boats and more sophisticated and robust gear. Reductions in fish catchability may be expressed via

- Increased storm activity – may reduce suitable days for activity
- Increased wave activity – may impact vessel and shore-based fishers
- Changes in seasonality – reduction in period when activity can occur, particularly if open seasons are not amended to account for seasonality changes.

Adaptation Options

Current Options for Dealing with Climate Variability

The current options for dealing with climate variability will be discussed separately for wild fisheries and for aquaculture. At this time for both fisheries and aquaculture, climate variability is just part of the “environment”, and most operators and managers do not deal explicitly with variability, beyond responding to the observed patterns. Within each sector, however, there are common approaches across regions, and thus the geographical approach of earlier sections is not followed here. This approach also allows insight to be gained for fisheries that are not explicitly covered in this review.

1. Fisheries

Fishers have had to cope with changes in abundance and distribution of key species in many regions, such as the south east (e.g. Smith & Smith 2001). The western rock lobster industry already copes with significant interannual catch fluctuations, as discussed earlier, and utilises a catch prediction system that allows industry to prepare for harvests several years ahead. Salmon abundance also varies along the southwest coast of Australia, and boom and bust years also occur in the scallop sector. In boom and bust fisheries, one adaptation strategy is to target different species in different years. Climate change may lead to additional changes in the alternative species harvested when the primary species is less available. Thus, the robustness of fishery sectors, such as the western zone, may decline in future if climate variability increases, as variation in catch between years will increase. Interaction between the commercial and recreational sector and other marine users are also resulting in zoning that excludes fishing activities in some areas (e.g. recreational fishing zones, marine protected areas).

Fishers often exhibit considerable fish finding skills. Their target species roam widely, and are subject to considerable interannual fluctuations in distribution and relative abundance. To counter this variability, fishers use a range of environmental products, such as satellite information and sophisticated on-board electronic equipment. These help them to locate suitable conditions for the species that is being targeted. Continued use and improved availability of these products and development of new predictive tools may improve the capacity of the fishers, providing the stocks can sustain the continued or enhanced harvests. In some fisheries, spotter planes also reduce the search time by locating schools of fish (e.g. northern prawn in southern Gulf of Carpentaria, southern bluefin tuna in the Great Australian Bight, skipjack tuna on the east coast of Australia).

Current approaches for dealing with changes in fisheries as a result of climate variability include; changes in fishing ports used, changes in fishery areas, changes in the quota allocated for harvest, and closures in some fisheries or fishing areas. The only Australian example (and perhaps internationally) where environmental information is incorporated into a management response that accounts for seasonal and interannual climate variability is in the east coast pelagic longline fishery. Southern bluefin tuna (*T. maccoyii*, SBT) are restricted to the cooler waters south of the East Australian Current and range further north when the current contracts up the New South Wales coast (Majkowski et al. 1981, Hobday & Hartmann 2006). This response to climate variability has allowed real-time spatial management to be used to restrict catches of SBT by non-quota holders in the east coast fishery by restricting access to ocean regions believed to contain SBT habitat (Hobday & Hartmann 2006). This habitat prediction is based on the relationship between water temperature (from the surface to 200 m) and the abundance of SBT. The current distribution of the tuna habitat is derived with a near-real time ocean model and then relayed to management during the fishing season. As the distribution of the SBT habitat changes during the season, management adjusts the location of restricted access areas throughout the season.

2. Aquaculture

Climate variability is a fact of life for many operators in the aquaculture sector. While the environment is regulated for some stages of a species life history (e.g. indoor hatcheries for salmon, abalone), the adults are usually exposed to a more natural environment. Even in this more natural environment, attempts are made to reduce the effects of climate variability via feeding (e.g. salmon, barramundi, prawns), cleaning or removal of competitors (e.g. pearl oysters), and thinning conspecifics (e.g. oysters and mussels).

Responses to climate variability also occur during or after the “climate” event, such as treatment for disease. In the Atlantic salmon industry, the prevalence of a gill disease is increased in warm water, and bathing in fresh water is used as a treatment. In warmer summers, increased bathing is used to combat outbreaks.

Selective breeding is the other major adaptation attempt. There is considerable effort in the aquaculture industry for developing strains with increased biological performance (e.g more robust stocks with fast growth).

The use of information on climate variability is limited, although many in the industry recognize that improved use of the available information will assist overall economic performance.

Adaptation Options for Dealing with Climate Change

The fisheries and aquaculture sectors are just beginning to develop strategies for climate change, and these efforts will gain momentum in the near future. The adaptation options are best illustrated with several examples of how fisheries or aquaculture may respond to climate change. Additional solutions will be developed as awareness increases, and this section is designed to stimulate additional ideas for adaptation options.

Climate change adaptation options for the fisheries sector have been seen mostly in the context of management options, including building resilience through improved stock status (e.g. Jackson et al 2001; Steneck et al 2002). Climate change impacts on exploited species could directly affect Australian fisheries management in several ways, including setting of climate regime-specific reference points, spatial management (including closures), and predictive models for harvest levels (Hobday et al 2007b). For example the Commonwealth harvest strategy policy sets certain benchmarks to define overfishing, including biomass limit reference points (Rayns 2007). These could well change as productivity or distribution change, with significant impacts on quotas and effort levels given the direct link between the benchmarks and management decisions. The guidelines to the policy already envisage that account should be taken of changing benchmarks, but the difficulty will be in detecting the effects and determining the changes (Hobday et al 2007b). Another management issue is that most fisheries are defined by jurisdictional boundaries that determine access and property rights. As species distributions change, fishers' rights may diminish, while other fishers currently without species access rights may gain effective access to the fish. Management policies can differ between regions: movement of stocks to areas without adequate management may also lead to resource conflict (Miller 2007, Stenevik & Sundby 2007). Proactive policy development is needed to avoid such conflict.

Changes in the abundance of species that are already at low historic levels (e.g. southern bluefin tuna) can be positive or negative. In the case of increased abundance (population recovery), rapid industry adaptation will be likely – driven by economic opportunity. It will be a challenge to determine if the change in abundance is likely to be sustained, or is due to interannual variability. This distinction is crucial for long-term business decisions around say, increasing fleet capacity or making technological investments. In the case of declining abundance, industry may be forced to adopt additional management measures to protect a particular species, and so may have reduced flexibility to target the non-impacted species. Thus adaptation options that reduce non-target capture will be useful in a changing climate, as well as improve the sustainability of fisheries in general.

As illustrative examples, we discuss three options for different sectors dealing with climate change. These are not exhaustive or even comprehensive, and serve merely as a guide to potential adaptation strategies.

Option 1 - Aquaculture –rising temperature in southern Australia

The aquaculture industry has several options for adaptation to climate change including selectively breeding for tolerance to altered temperature regimes or the use of alternate species that are pre-adapted to the temperature regimes; and relocation of production facilities, including the movement of cage systems to deeper offshore waters (Preston and Poloczanska 2007).

The predicted temperature change in waters around Australia over the coming century is relatively slow compared to the generation times of the Australian aquaculture species that are currently considered amenable to selective breeding; these range from a year or less for prawns (Preston et al. 2004), two years for oysters (Appleyard et al. 2006) to three years for Atlantic salmon (Elliott & Riley 2003) and temperate abalone (Shepherd et al. 1974). Although there appears to be significant potential to adapt these aquaculture species to changes in temperature within appropriate time frames, whether this is possible will depend on the genetic diversity of the breeding population. The development of new aquaculture species to meet the growing demand for seafood products will also increase adaptability of aquaculture industries to climate change, however, the choice of new species is not independent of markets, competitors, and biological limitations (Preston and Poloczanska 2007).

Impacts can be mitigated to some extent by foresight in planning and selection of sites and of species. Rapid response to the projected warming can be achieved in farming of caged fish, such as salmon, by moving cages offshore to deeper, cooler waters. There is increasing global interest in offshore aquaculture for a number of reasons, including the need to avoid adverse impacts on fish health and quality from pollutants discharged into coastal waters (Ryan 2004). Ameliorating, the impacts of climate change, particularly for species at the limits to their thermal tolerance, may provide additional incentive to develop offshore aquaculture technology.

Option 2 – Following the fish – changes in distribution of pelagic species

For pelagic fisheries, most of the immediate impacts of climate change will be expressed as changes in distribution of the target stocks (Hobday et al 2007b). As a result, the potential adaptation options devised to date are mostly around changing distributions. Adaptation strategies include: improvements in locating stocks of fish, changes in home port to increase or minimise economic costs associated with transport, and zoning of fish habitats to minimise unwanted species interactions.

Fishers often use a range of ports along the coast, and change location during the season as fish distribution or availability changes. Infrastructure may vary between these ports, such as the number of berths, storage facilities, ship chandleries, and transport links. Processing facilities and airlinks are considered the main bottlenecks. If ports receive only occasional usage by some boats, then infrastructure is not stretched, however, if major changes in the usage resulted from changed distribution of the catch, infrastructure may prove to be inadequate in new areas (Hobday et al 2007b).

Changes in species distributions where stocks become more separated may reduce the restrictions introduced when species overlap. For example, a southward contraction in the distribution of southern bluefin tuna (SBT) on the east coast of Australia would allow longline fishers targeting other species to fish more freely areas previously occupied by SBT (Hobday and Hartmann 2006), which may be an economic advantage.

As climate-driven changes in fish distribution occur, however, commercial fishers may not be able to simply follow the stocks as they may contract into different management regions. Information on the potential changes will enhance industry capability to adapt to climate change, and make sensible business and investment decisions. This information does not always exist, and where it does, it may not be accessible to those who need it.

Option 3 – Ecosystem-based fishery management – climate change is part of the system

Ecosystem-based fisheries management (EBFM) takes into account interrelationships between exploited fish stocks, non-target species, the environment, and human action (e.g. Link et al 2002). The effect of climate on fisheries is recognised as important in this approach, and adaptation options are being explored within ecosystem models (B. Fulton, pers. comm). Ecosystems are extremely complex and current challenges include defining ecosystem and fisheries objectives to be conserved or met, as well as defining indicators, reference points and implementation mechanisms. The transition to

EBFM may entail short-term costs and sacrifices by the fishing industry but these will be out-weighed by longer term benefits. In one example, the Northern Prawn Fishery is moving to ecosystem based management through the Northern Prawn Fishery Management Plan (1995) which implements various fishery effort, target species and bycatch species limits.

Such holistic approaches to fishery management will also increase industry adaptation in the face of climate change, as increased attention to EBFM is expected to increase resilience of fisheries to a range of impacts. Other holistic approaches, including the CSIRO Ecological Risk Assessment for the Effects of Fishing (Hobday et al 2007a), also support the EBFM approach, and could be adapted to provide estimates of risks due to climate change. It is recognized that adapting to climate change will most successful when undertaken in conjunction with existing strategies (Smit and Wandel 2006), such as EBFM.

Adaptation options under the EBFM umbrella include developments in bycatch reduction, and improved targeting practises that will have the dual benefit of minimising impacts on non-target species, and provide potential alternatives to spatial closures to protect the particular species. Multi-species fisheries should continue to develop species-specific fishing gears and targeting practices to improve future adaptability. Species-specific gears will allow individual species to be targeted, without impacting other species that may be in decline due to climate change, and protected from fishing.

This move in Australia to EBFM is illustrative for climate adaptation, because it entails explicit recognition for the importance of understanding environmental relationships. Thus, an EBFM approach will also facilitate adaptation to climate change through the holistic approach (Smit and Wandel 2006).

Option 3 – Recreational and indigenous fishers

Recreational and indigenous fishers are increasingly aware that they may have a significant impact on biological populations. As a result of climate change, management of the fisheries may change. For example, recreational fishers may advocate changes to bag or size limits. They may also advocate increased support for research through licence fees, or offer targeted collection or reporting to supplement the knowledge base on particular species. Although Henry and Lyle (2003) report that the motivation of many recreational fishers is not to provide food, fishing is unlikely to take place in the absence of fish. Thus, changes in fish abundance or distribution will be a concern to fishers.

Indigenous fishers, particularly those harvesting the same species as commercial operators may seek greater involvement in integrated management, and support a reduction of fishing pressure on impacted species.

Both groups will be impacted by changes in the physical environment, and must advocate that vessel and shore-based safety regulations are adhered too, support increased use of ocean forecasts, and become active in fisher education to increase awareness of environmental changes.

There may be opportunities for business in new regions, and for longer seasons in the same regions. For example, game fishing targets “warm water species”, so southward movements due to ocean warming may be an advantage with regard to longer fishing seasons, and increased availability to the south.

Risks of Maladaptation

While the potential for maladaptation exists in future strategies, the development of adaptation strategies is in the early stages for Australian fisheries and aquaculture. At this time, recognition that some strategies may have unintended consequences for climate change is an important point to make. A few speculative suggestions of potential maladaptation are offered as illustrations rather than case studies.

1. Fisheries

One risk of maladaptation is via potential relaxation of spatial management regulations. This may not lead to fishers following climate-driven spatial changes in "peak abundance" as desired; it may lead instead to serial depletion of separate stocks. This risk exists because information on fish distribution and response to climate is lacking. An adaptation response that includes reduced spatial restriction for fishers should be preceded by studies on stock responses to changing environmental conditions, fish movement responses to the environment, and fisher behavior.

Relaxation of spatial restrictions of some fishing activities may have unforseen consequences. For example, the cost of fuel is a large proportion of the financial cost of fishing and one that is likely to increase in the future as diminishing reserves and increasing demand drive up the price of fossil fuels. Increased travel distances as new areas are opened, fish stocks shift or diminish, and projected increases in ocean storminess (hence lengthening travel times), together with burgeoning fuel costs may lead to further economic crises in fisheries. In 2000, global fisheries were estimated to have burned 50 billion litres of fuel, accounting for 1.2% of global oil consumption – equivalent to the amount burned by the 18th ranked oil consuming country globally – and emitted over 130 million tonnes of CO_2 into the atmosphere (Tyedmers et al 2005). Given the reliance of the modern fishing fleet on fossil fuels, future management and policy will need to consider reducing these costs. Providing suitable infrastructure at a range of ports could reduce the reliance on long journeys to a, say, a single landing and processing facility.

2. Aquaculture

Aquaculture currently accounts for almost 50 percent of the world's food fish and has the potential to meet the estimated demand for the additional 40 million tonnes of aquatic food that will be required by 2030 to maintain the current per capita consumption (FAO 2006). Of concern is the potential impact of climate change on the supply of aquaculture-feed ingredients. Feeds used in the culture of carnivorous fishes (e.g. salmon and barramundi) and crustaceans (e.g. prawns) generally contain high concentrations of protein, much of which is at present obtained through the inclusion of wild-harvest fish (Preston and Poloczanska 2007). Expansion of aquaculture industries is placing increasing demand on global supplies of wild-harvest fishmeal to provide protein and oil ingredients for aqua-feeds. The potential for adverse impacts of climate change on global fishmeal production is well illustrated by periodic shortages associated with climate fluctuations such as El Niño (e.g. Barlow 2002). Irrespective of the impacts of climate change, production of fish meal and fish oil from the oceans is likely to decline as demand increases. Over the past 20 years, efforts to find cost-effective alternatives have centered on proteins from terrestrial plants, particularly soy bean meal. If, as seems likely, that the use of soy bean meal and other terrestrial plant proteins increases, then the impacts of climate change on national and global terrestrial crop plant industries will become increasingly relevant for finfish and crustacean aquaculture (Preston and Poloczanska 2007).

Costs and Benefits

Climate change will impact the biological, economic and social aspects of many fisheries; and both positive and negative impacts are expected. Fisheries will be impacted differently according to the physical changes in the regional environment, for example, south-east fisheries are most likely to be affected by changes in water temperature, northern fisheries by changes in precipitation, and western fisheries by changes in the Leeuwin Current (Voice et al 2006, Hobday et al 2007b). Wild fisheries will see increased opportunity where tropical species move southward, while for southern fisheries, reconciling non-climate threats with increasing temperature will require proactive management (Hobday et al 2007b). With regard to socio-economic impacts, aquaculture industries have considerable adaptation potential via selective breeding, regulating the environment, and new species opportunities (Preston and Poloczanska 2007). Management structures and policies that account for climate change will allow most flexibility in adapting to future patterns.

In common with other food production sectors, climate change is likely to have direct and indirect impacts on all Australian aquaculture production environments (Preston and Poloczanska 2007). These include freshwater ponds, brackish water and marine ponds, and industries that use rafts, lines or cages in coastal or offshore waters. Given the projected impacts of climate change on freshwater supplies in Australia (Hennessey et al. 2007), freshwater aquaculture industries may be the most vulnerable. Conversely, pond-based or open water marine aquaculture sectors could perceivably benefit from climate change and be well placed to respond to the global demand for aquatic food. Climate change is likely to favour the development of new industries such as microalgae biomass production. The emergence of global interest in the potential for mass cultivation of microalgae as a source of biofuels, feeds, chemicals, pharmaceuticals and nutraceuticals (Benemann 1992, Borowitzka 1997, Spolaore et al. 2006, Chisti 2007) could provide an opportunity for Australia to take advantage of increased solar radiation and elevated temperatures. The development of this new aquaculture sector could be particularly significant if mass cultivation of microalgae proves to be an effective method of post-combustion of CO_2 from Australia's coal fired power stations (Kaddam 1997, de Morais and Costa 2007).

The impacts of climate change on aquaculture are likely to heighten public awareness of the need to respond to the changes. As many aquaculture ventures are in public waterways, acute impacts - such as the farmed tuna mortalities noted earlier - are likely to be highly visible. This increased awareness could lead to more concerted efforts to rigorously assess and predict the likely impacts of climate change on aquaculture. At the same time, quota reductions in the wild capture fisheries are having major impacts on the economic viability of coastal communities outside the cities; aquaculture is one of the few alternative sources of employment generally available in coastal towns. The interaction of social and economic factors in relation to climate impacts and setting public policy has yet to be played out.

Knowledge Gaps and Priorities

It has been recognized for over 100 years that oceanic processes, for example advection and water temperature affect biological processes such as recruitment to fish stocks (e.g. Hjort 1914; Hannesson 2007). Recent progress has been made in the northern hemisphere on the influence of climate change on such processes (e.g. Clark et al 2003; Rose, 2004; Drinkwater 2005; Perry et al 2005). Considerable progress is also being made through research on the role of climate variability (such as El Niño – Southern Oscillation events) in influencing biological processes (e.g. Lehodey et al 1997), which will inform how climate change may impact fish stocks. This approach typically requires time-series of biological and physical data covering more than one cycle of the climate variability pattern. Climate variability usually operates on shorter time-scales, such as annual or decadal, while climate change operates over many decades or longer.

The evidence for climate change impacts on Australian marine fisheries so far, has been largely inferred from studies of climate variability (Hobday et al 2007b). This is because (i) climate change scenarios for the coastal and pelagic environments have, until recently, lacked the spatial resolution necessary for biological studies, and (ii) most fisheries and their captured species are not amenable to experimental manipulation, and so climate change impacts cannot be readily measured as for some terrestrial or benthic systems such as coral. Further, Australia suffers from a lack of long-term data for most fisheries, which hinders research into climate impacts, despite more then a century of exploitation in some regions. Fishers were not required to complete fishery logbooks until comparatively recently; the logbooks are the most common data source used to assess resource abundance. Fishery-independent sampling is far less common. Australia's participation in several international programs focused on the climate impacts on fished species may help to overcome the temporal limitation by enabling spatial comparisons between regions. Two such programs are the GLOBEC (Global Ocean Ecosystem Dynamics) initiatives SPACC (Small Pelagics and Climate Change) and CLIOTOP (Climate Impacts on Top Ocean Predators). This Australian contribution to these international efforts will likely increase in the coming years.

In future, information on the biological relationships with climate variability must be collected to give insight into the impacts of climate change on fisheries and aquaculture. With additional information, assessments of future impacts can be made with greater confidence and management responses can be justified to sometimes reluctant stakeholders. Retrospective analyses, including paleo-ecological studies, will continue to be crucial in resolving physical-biological relationships, with ocean models providing previously missing or unattainable environmental data (Hobday et al 2007c). The research partnership between climate modellers and fisheries and aquaculture scientists must be fostered to ensure that biologically relevant information at desirable spatial and temporal scale will be available from the climate models.

Immediate progress with maximum reward can be made by undertaking focused regional studies. Hobday et al (2007b) recommended several studies that may provide rapid insight and generate improved understanding of climate change threats, opportunities and adaptation strategies.

- Investigation of climate impacts on south-east demersal fisheries. The relatively long biological time-series already in existence and documented range changes suggest this is an area where clear impact will occur. The south-east area is also the region where climate models indicate rapid warming (Tasman Sea warming), and considerable social disruption would occur if key fisheries were affected. It is important to consider the potential for mitigation or adaptation to any anticipated change. Fisheries and the management approach in this region are also undergoing major restructuring and have shown willingness to consider climate information in setting catch levels. In part due to this recommendation for a south-east focus, the Australian Greenhouse Office through its Coastal Vulnerability Adaptation Program has selected the east coast of Tasmania as one of the six regional case studies. The impact of climate change on a fishery in this region will be investigated in 2008.

- Investigation of climate impacts on western rock lobster. The recruitment link currently used by management to set quotas is a statistical relationship whose mechanism is not fully understood. If climate change leads to decoupling of this link, such that the adult biomass is no longer well predicted by larval settlement, then the current management regime may be compromised, and a valuable and high-profile industry impacted. Elucidating the role of climate variability in this fishery would support a sustainable future. By investigating and identifying the mechanistic link between the Leeuwin Current and rock lobster settlement, one would obtain the essential information to assess climate-change impacts on the rock lobster fishery. Such work would be critical to addressing the impacts of climate change within the management framework of the rock lobster fishery and to ensuring a sustainable future fishery. Research on the Leeuwin Current-rock lobster link would also benefit other fisheries in Western Australia.

- Investigation of socio-economic impacts of climate on fisheries and aquaculture. A regional focus study, such as on the Eastern Tuna and Billfish Fishery, where environmental variability is a key driver of fishing effort, or on an aquaculture industry such as salmon farming, would allow development of integrated models predicting how the socio-economic impacts of climate change will be felt. This challenging area would require partnerships between biologists, social scientists, economists and ocean modellers from a range of Australian organisations.

- Investigation of changes in productivity around Australia. Current ocean forecasts focus on physical changes; the crucial next step is to forecast change at the base of the food chain. For example, changes in upwelling and mixing may impact regional productivity and thus the range and distribution of key species that occur across a variety of fisheries.

Table 12.3: Summary of climate change adaptation options for Australian fisheries and aquaculture indicating whether the option 1) has already been assessed or is a remaining knowledge gap, 2) is highly feasible, 3) would be feasible / effective immediately, or 4) should be a high priority for research, assessment and implementation in developing adaptation strategies.

Adaptation options	Options already assessed	Options with high feasibility	Immediacy	Priority activities
Policy level				
Develop linkages to existing government policies and initiatives e.g. GGAP, Greenhouse challenge, salinity, water quality, rural restructuring				
Fisheries	X	X	✓	✓
Aquaculture	X	✓	✓	✓
Ensure communication of broader climate change information				
Fisheries	?	✓	✓	✓
Aquaculture	?	✓	✓	✓
Maintenance of effective climate data distribution and analysis systems				
Fisheries	X	✓	X	✓
Aquaculture	X	✓	X	✓
Continue training to improve self-reliance and to provide knowledge base for adapting				
Fisheries	X	✓	X	X
Aquaculture	X	✓	✓	✓
Increase R&D capacity, undertake further adaptation studies which include costs/benefits and streamline rapid R&D responses				
Fisheries	?	?	✓	✓
Aquaculture	✓	✓	✓	✓
Develop further harvest modelling capabilities and quantitative approaches to risk management				
Fisheries	✓	✓	✓	✓
Aquaculture	?	✓	?	?
Encourage appropriate management, policy, and industry structures to enable flexibility				
Fisheries	X	?	✓	✓
Aquaculture	X	✓	✓	✓
Encourage diversification of enterprises (e.g. ecotourism, scientific charters, recreational fishers)				
Fisheries	?	✓	✓	X
Aquaculture	?	✓	?	X
Ensure support during transition periods caused by				

Adaptation options	Options already assessed	Options with high feasibility	Immediacy	Priority activities
climate change and assist new industry establishment or exit from the industry				
Fisheries	✓	?	✓	✓
Aquaculture	?	?	?	?
Altering transport and market infrastructure to support altered production regimes caused by climate change				
Fisheries	X	?	X	X
Aquaculture	?	?	?	?
Introduction of climate change adaptation into Ecosystem-based Fisheries Management, and regional management plans				
Fisheries	?	?	✓	✓
Aquaculture	?	?	✓	✓
Climate information and use				
Improve dynamic climate modelling tailored towards decision making				
Fisheries	?	✓	?	✓
Aquaculture	?	✓	?	✓
Incorporate seasonal forecasts and climate change into business plans to improve adaptive capacity				
Fisheries	?	✓	✓	✓
Aquaculture	?	✓	✓	✓
Development of tools and extension to enable operators to access climate data and interpret the data in relation to their harvest records and analyse alternative management options.				
Fisheries	?	?	?	?
Aquaculture	✓	✓	✓	✓
Warnings about likelihood of extreme events prior to decision making period				
Fisheries	?	?	?	?
Aquaculture	?	?	?	?
Target species issues				
Improve predictive tools and indicators for species impacted by climate change				
Fisheries	X	✓	✓	✓
Aquaculture	X	✓	✓	✓
Selection of varieties with appropriate physical tolerances and phenological characteristics	n/a	n/a	n/a	n/a

Adaptation options	**Options already assessed**	**Options with high feasibility**	**Immediacy**	**Priority activities**
Fisheries	✓	✓	✓	✓
Aquaculture				
Ongoing evaluation of climate relationships for key species (e.g. distribution, phenology/life history)				
Fisheries	✓	✓	✓	✓
Aquaculture	✓	✓	✓	✓
Flexibility to shift efforts between species (fisheries and aquculture) or genetic stocks (aquaculture) to take advantage of novel conditions (e.g. very warm year)				
Fisheries	?	?	?	?
Aquaculture	?	?	✓	✓
Ecosystem management				
Further development of regional management plans that are appropriate for the distribution of the species being harvested or farmed.				
Fisheries	?	✓	✓	✓
Aquaculture	✓	✓	✓	X
Develop precautionary approaches that reduce the risk of non-target impacts				
Fisheries	✓	✓	✓	✓
Aquaculture	✓	✓	✓	✓
Alter harvesting practices to be more opportunistic depending on environmental conditions (e.g. water temperature), climate (e.g. ENSO risk) and markets				
Fisheries	?	?	✓	X
Aquaculture	?	✓	✓	?
Improve pest and disease predictive tools and indicators				
Fisheries	X	✓	✓	✓
Aquaculture	✓	✓	✓	✓

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13: APPENDIX - OZCLIM CLIMATE CHANGE PROJECTIONS FOR SUGARCANE REGIONS

OZCLIM generates regional climate change scenarios based on the spatial patterns of change from 12 different Global climate models (GCMs) combined with 18 different greenhouse gas emission projections (IPCC, 2001). For the purposes of this review projections have been determined from regional patterns of projected climate change generated from the Hadley Centre (HADCM3) fully coupled model and CSIRO limited area model (DARLAM125) to examine a broad range of likely changes in temperature and rainfall at both 2020 and 2030. The regional patterns of change were scaled using a low future emission trajectory (A2) and high emission trajectory (A1T) for 2020 (Table 13:1) and 2030 (Table 13:2) (SRES, 2000). The relatively low temperature sensitivity to double CO_2 concentrations demonstrated by DARLAM meant scenarios produced by this model represented the lower end of projected changes (i.e. 2020 or 2030 low), whereas the HADCM3 projections more extreme projections or change (i.e. 2020 or 2030 high).

Table 13:1: Seasonal baseline (1961-1990 mean) maximum temperature (Tmax, °C), minimum temperature (Tmin, °C) and rainfall (R'fall, mm), and climate change projections for low and high emission scenarios for 2020 for Tmax (°C), Tmin (°C) and R'fall (%) for a range of locations in the Australian sugarcane industry.

		Baseline (1961-1990)					2020 low					2020 high				
		Summer	Autumn	Winter	Spring	**Annual**	Summer	Autumn	Winter	Spring	**Annual**	Summer	Autumn	Winter	Spring	**Annual**
Mossman	Tmin (°C)	19.0	17.1	12.6	16.0	**16.2**	0.3	0.4	0.3	0.4	**0.4**	1.0	0.9	0.8	0.8	**0.9**
	Tmax (°C)	27.8	24.2	21.4	26.3	**24.9**	0.3	0.3	0.3	0.4	**0.3**	1.0	0.8	0.8	0.8	**0.8**
	R'fall (mm/%)	1237.0	1022.0	247.0	304.0	**2810.0**	-1.4	1.4	0.0	-0.3	**-0.1**	-5.1	-2.7	-9.8	-13.3	**-5.5**
Mareeba	Tmin (°C)	20.5	17.8	12.4	16.4	**16.8**	0.3	0.4	0.3	0.4	**0.3**	0.9	0.9	0.8	0.8	**0.9**
	Tmax (°C)	29.8	26.6	23.8	28.4	**27.2**	0.3	0.3	0.3	0.4	**0.3**	0.9	0.8	0.8	0.7	**0.8**
	R'fall (mm/%)	628.0	421.0	67.0	116.0	**1232.0**	-1.6	1.4	0.3	-0.7	**-0.4**	-5.4	-3.9	-9.4	-15.1	**-6.0**
Babinda	Tmin (°C)	23.4	21.3	16.7	20.0	**20.4**	0.3	0.3	0.3	0.3	**0.3**	0.9	0.8	0.8	0.7	**0.8**
	Tmax (°C)	30.8	28.4	25.1	28.5	**28.2**	0.3	0.3	0.3	0.3	**0.3**	0.9	0.8	0.8	0.7	**0.8**
	R'fall (mm/%)	1610.0	1582.0	354.0	385.0	**3931.0**	-2.0	2.3	0.4	-0.8	**0.1**	-5.2	-2.7	-8.5	-13.1	**-5.3**
Tully	Tmin (°C)	22.9	20.5	15.0	19.2	**19.4**	0.3	0.3	0.3	0.3	**0.3**	1.0	0.9	0.9	0.8	**0.9**
	Tmax (°C)	31.3	28.7	25.2	29.2	**28.6**	0.3	0.3	0.3	0.3	**0.3**	1.0	0.8	0.9	0.8	**0.9**
	R'fall (mm/%)	1294.0	1244.0	274.0	300.0	**3112.0**	-2.5	2.7	1.0	-0.5	**0.1**	-4.4	-3.7	-7.6	-13.6	**-5.3**
Ingham	Tmin (°C)	23.8	20.8	14.9	20.1	**19.9**	0.3	0.4	0.4	0.3	**0.4**	1.0	1.0	0.9	0.9	**1.0**
	Tmax (°C)	32.0	29.5	25.8	29.9	**29.3**	0.3	0.4	0.3	0.4	**0.3**	1.1	0.9	0.9	0.9	**0.9**
	R'fall (mm/%)	1003.0	642.0	94.0	185.0	**1924.0**	-2.1	2.7	1.4	-0.9	**-0.2**	-5.0	-5.7	-6.5	-14.4	**-6.2**
Ayr	Tmin (°C)	23.3	20.0	14.0	19.1	**19.1**	0.3	0.4	0.4	0.3	**0.3**	1.0	1.0	0.9	0.9	**1.0**
	Tmax (°C)	31.6	28.9	25.1	29.5	**28.8**	0.3	0.3	0.3	0.3	**0.3**	1.1	0.9	0.9	0.9	**0.9**
	R'fall (mm/%)	587.0	328.0	72.0	94.0	**1081.0**	-1.6	4.2	1.5	-0.8	**0.5**	-4.9	-5.6	-6.8	-13.9	**-6.0**

		Baseline (1961-1990)					2020 low					2020 high				
		Summer	Autumn	Winter	Spring	**Annual**	Summer	Autumn	Winter	Spring	**Annual**	Summer	Autumn	Winter	Spring	**Annual**
Proserpine	Tmin (°C)	22.3	18.7	12.0	17.6	**17.7**	0.4	0.4	0.4	0.4	**0.4**	1.1	1.0	1.0	1.0	**1.0**
	Tmax (°C)	30.7	27.6	23.4	28.3	**27.5**	0.3	0.4	0.3	0.4	**0.3**	1.1	0.9	0.9	0.9	**1.0**
	R'fall (mm/%)	800.0	462.0	99.0	146.0	**1507.0**	-0.8	4.1	1.4	-0.8	**0.9**	-3.9	-6.0	-7.9	-13.1	**-5.7**
Mackay	Tmin (°C)	23.5	20.0	13.6	19.5	**19.1**	0.3	0.4	0.3	0.4	**0.4**	1.1	1.0	1.0	1.0	**1.0**
	Tmax (°C)	30.4	27.2	22.6	27.8	**27.0**	0.3	0.4	0.3	0.4	**0.3**	1.1	0.9	1.0	1.0	**1.0**
	R'fall (mm/%)	837.0	548.0	123.0	176.0	**1684.0**	-0.3	3.5	1.8	-1.2	**1.0**	-2.5	-5.8	-9.3	-13.1	**-5.2**
Bundaberg	Tmin (°C)	21.6	18.1	11.7	17.2	**17.1**	0.4	0.4	0.3	0.4	**0.4**	1.0	0.9	0.9	1.0	**1.0**
	Tmax (°C)	30.2	27.3	22.6	27.1	**26.8**	0.3	0.4	0.3	0.3	**0.3**	1.1	0.9	1.0	1.0	**1.0**
	R'fall (mm/%)	459.0	276.0	143.0	192.0	**1070.0**	0.8	1.3	2.1	-0.7	**0.8**	-1.4	-7.7	-7.7	-9.5	**-5.3**
M'borough	Tmin (°C)	20.6	16.8	9.5	15.2	**15.5**	0.4	0.4	0.3	0.3	**0.4**	1.0	0.9	0.9	1.0	**0.9**
	Tmax (°C)	29.8	26.7	22.2	27.1	**26.5**	0.3	0.4	0.3	0.3	**0.3**	1.0	0.8	0.9	1.0	**0.9**
	R'fall (mm/%)	476.0	305.0	178.0	225.0	**1184.0**	0.2	1.1	2.6	-0.6	**0.7**	-1.0	-8.2	-7.8	-9.5	**-5.5**
R Point	Tmin (°C)	19.7	16.1	9.4	14.7	**15.0**	0.3	0.4	0.3	0.3	**0.3**	0.9	0.8	0.9	0.9	**0.9**
	Tmax (°C)	28.5	25.5	20.9	25.2	**25.0**	0.3	0.4	0.3	0.3	**0.3**	1.0	0.9	0.9	1.0	**0.9**
	R'fall (mm/%)	494.0	419.0	215.0	252.0	**1380.0**	0.5	0.9	2.1	-0.4	**0.7**	-1.7	-10.3	-9.1	-9.9	**-7.0**

Table 13:2: Seasonal baseline (1961-1990 mean) maximum temperature (Tmax, °C), minimum temperature (Tmin, °C) and rainfall (R'fall, mm), and climate change projections for low and high emission scenarios for 2030 for Tmax (°C), Tmin (°C) and R'fall (%) for a range of locations in the Australian sugarcane industry.

		Baseline (1961-1990)					2030 low					2030 high				
		Summer	Autumn	Winter	Spring	**Annual**	Summer	Autumn	Winter	Spring	**Annual**	Summer	Autumn	Winter	Spring	**Annual**
Mossman	Tmin (°C)	19.0	17.1	12.6	16.0	**16.2**	0.4	0.6	0.5	0.5	**0.5**	1.4	1.3	1.2	1.2	**1.3**
	Tmax (°C)	27.8	24.2	21.4	26.3	**24.9**	0.4	0.4	0.5	0.5	**0.5**	1.4	1.2	1.2	1.1	**1.2**
	R'fall (mm/%)	1237.0	1022.0	247.0	304.0	**2810.0**	-2.1	2.0	0.1	-0.4	**-0.2**	-7.4	-4.0	-14.3	-19.5	**-8.1**
Mareeba	Tmin (°C)	20.5	17.8	12.4	16.4	**16.8**	0.4	0.5	0.5	0.5	**0.5**	1.4	1.3	1.2	1.2	**1.3**
	Tmax (°C)	29.8	26.6	23.8	28.4	**27.2**	0.4	0.5	0.5	0.5	**0.5**	1.4	1.2	1.2	1.1	**1.2**
	R'fall (mm/%)	628.0	421.0	67.0	116.0	**1232.0**	-2.4	2.1	0.4	-1.1	**-0.6**	-8.0	-5.7	-13.8	-22.1	**-8.8**
Babinda	Tmin (°C)	23.4	21.3	16.7	20.0	**20.4**	0.4	0.5	0.5	0.5	**0.5**	1.3	1.2	1.2	1.1	**1.2**
	Tmax (°C)	30.8	28.4	25.1	28.5	**28.2**	0.4	0.4	0.5	0.5	**0.4**	1.3	1.1	1.2	1.1	**1.2**
	R'fall (mm/%)	1610.0	1582.0	354.0	385.0	**3931.0**	-2.8	3.4	0.6	-1.2	**0.1**	-7.7	-4.0	-12.4	-19.2	**-7.8**
Tully	Tmin (°C)	22.9	20.5	15.0	19.2	**19.4**	0.4	0.5	0.5	0.5	**0.5**	1.4	1.3	1.3	1.2	**1.3**
	Tmax (°C)	31.3	28.7	25.2	29.2	**28.6**	0.4	0.5	0.5	0.5	**0.5**	1.4	1.2	1.3	1.2	**1.3**
	R'fall (mm/%)	1294.0	1244.0	274.0	300.0	**3112.0**	-3.6	3.9	1.5	-0.8	**0.1**	-6.4	-5.5	-11.2	-19.9	**-7.8**
Ingham	Tmin (°C)	23.8	20.8	14.9	20.1	**19.9**	0.5	0.5	0.5	0.5	**0.5**	1.5	1.4	1.4	1.3	**1.4**
	Tmax (°C)	32.0	29.5	25.8	29.9	**29.3**	0.4	0.5	0.5	0.5	**0.5**	1.6	1.3	1.3	1.3	**1.4**
	R'fall (mm/%)	1003.0	642.0	94.0	185.0	**1924.0**	-3.0	4.0	2.0	-1.3	**-0.3**	-7.4	-8.3	-9.5	-21.1	**-9.1**
Ayr	Tmin (°C)	23.3	20.0	14.0	19.1	**19.1**	0.5	0.5	0.5	0.5	**0.5**	1.5	1.4	1.4	1.3	**1.4**
	Tmax (°C)	31.6	28.9	25.1	29.5	**28.8**	0.4	0.5	0.5	0.5	**0.5**	1.6	1.3	1.4	1.3	**1.4**
	R'fall (mm/%)	587.0	328.0	72.0	94.0	**1081.0**	-2.3	6.1	2.3	-1.1	**0.7**	-7.1	-8.3	-10.0	-20.3	**-8.8**

		Baseline (1961-1990)					2030 low					2030 high				
		Summer	Autumn	Winter	Spring	**Annual**	Summer	Autumn	Winter	Spring	**Annual**	Summer	Autumn	Winter	Spring	**Annual**
Proserpine	Tmin (°C)	22.3	18.7	12.0	17.6	**17.7**	0.5	0.6	0.5	0.6	**0.5**	1.5	1.4	1.4	1.4	**1.4**
	Tmax (°C)	30.7	27.6	23.4	28.3	**27.5**	0.4	0.5	0.5	0.5	**0.5**	1.6	1.3	1.4	1.4	**1.4**
	R'fall (mm/%)	800.0	462.0	99.0	146.0	**1507.0**	-1.1	6.0	2.1	-1.1	**1.3**	-5.8	-8.8	-11.6	-19.1	**-8.4**
Mackay	Tmin (°C)	23.5	20.0	13.6	19.5	**19.1**	0.5	0.6	0.5	0.6	**0.5**	1.6	1.4	1.4	1.5	**1.5**
	Tmax (°C)	30.4	27.2	22.6	27.8	**27.0**	0.4	0.5	0.5	0.5	**0.5**	1.6	1.3	1.4	1.4	**1.4**
	R'fall (mm/%)	837.0	548.0	123.0	176.0	**1684.0**	-0.5	5.1	2.7	-1.7	**1.4**	-3.7	-8.5	-13.7	-19.1	**-7.6**
Bundaberg	Tmin (°C)	21.6	18.1	11.7	17.2	**17.1**	0.5	0.6	0.5	0.5	**0.5**	1.5	1.3	1.3	1.5	**1.4**
	Tmax (°C)	30.2	27.3	22.6	27.1	**26.8**	0.4	0.6	0.4	0.5	**0.5**	1.5	1.3	1.4	1.5	**1.4**
	R'fall (mm/%)	459.0	276.0	143.0	192.0	**1070.0**	1.2	1.9	3.0	-1.0	**1.2**	-2.0	-11.3	-11.3	-14.0	**-7.8**
M'borough	Tmin (°C)	20.6	16.8	9.5	15.2	**15.5**	0.5	0.6	0.5	0.5	**0.5**	1.4	1.2	1.3	1.4	**1.3**
	Tmax (°C)	29.8	26.7	22.2	27.1	**26.5**	0.4	0.6	0.4	0.5	**0.5**	1.5	1.2	1.4	1.4	**1.4**
	R'fall (mm/%)	476.0	305.0	178.0	225.0	**1184.0**	0.4	1.6	3.8	-0.8	**1.0**	-1.5	-12.0	-11.4	-13.8	**-8.1**
R Point	Tmin (°C)	19.7	16.1	9.4	14.7	**15.0**	0.5	0.6	0.5	0.4	**0.5**	1.4	1.2	1.3	1.4	**1.3**
	Tmax (°C)	28.5	25.5	20.9	25.2	**25.0**	0.4	0.6	0.4	0.5	**0.5**	1.4	1.3	1.4	1.5	**1.4**
	R'fall (mm/%)	494.0	419.0	215.0	252.0	**1380.0**	0.7	1.4	3.1	-0.5	**1.1**	-2.5	-15.1	-13.4	-14.5	**-10.2**