



Department of
Agriculture and Food



Climate change: impacts and adaptation for agriculture in Western Australia

Bulletin 4870

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Department of
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and Ian Foster**

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April 2016

ISSN 1833-7236

Cover: Tincurrin rainbow (photo: R Sudmeyer)

Recommended reference

Sudmeyer, R, Edward, A, Fazakerley, V, Simpkin, L & Foster, I 2016, 'Climate change: impacts and adaptation for agriculture in Western Australia', *Bulletin 4870*, Department of Agriculture and Food, Western Australia, Perth.

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Acknowledgements

We thank Imma Farre and Dennis van Gool for providing updated maps and information relating to wheat yields under future climates and Mitch Lever for providing information about biofuels. We thank James Duggie, Sarah Gill, Meredith Guthrie, Fiona Jones, Brad Plunkett, John Ruprecht and Mark Seymour for providing valuable comment to improve this review. We also thank Kathryn Buehrig and Angela Rogerson for editing this bulletin.

Summary

The Department of Agriculture and Food, Western Australia (DAFWA) is actively working to reduce the vulnerability of the agricultural sector to climate variability and change and to increase the sector's adaptive capacity. In 2010, DAFWA developed a 'Climate change response strategy' to provide strategic direction for climate change activities and to identify and prioritise actions to achieve over the following five years. Since the strategy was published, there have been considerable advances in the scientific understanding of climate change. This bulletin reviews the latest scientific information relating to climate change and agriculture in Western Australia (WA).

Climate change is affecting Australia's natural environment and the human systems it supports. Over the last 100 years, WA's average annual temperature has increased by about 1 degree Celsius (°C). Rainfall has increased slightly in the north and interior but it has declined significantly along the west coast and in the south-west. Drier conditions have increased frost risk in central and eastern areas of the wheatbelt and increased fire risk throughout the state. There is overwhelming scientific consensus that human activities, particularly those increasing atmospheric greenhouse gas concentrations, are contributing to these changes by altering the global energy budget and climate.

The peer reviewed, scientific literature indicates a consensus understanding that unless global efforts to reduce the emission of greenhouse gases are rapidly and greatly increased, the effects of climate change may be profound. International ambitions to limit global warming to less than 2°C are beginning to appear increasingly difficult to achieve. A world that is more than 2°C warmer will pose many challenges for human society. Reducing greenhouse gas emissions and maintaining the atmospheric carbon dioxide (CO₂) concentration below 450 parts per million (ppm) remains the best way to limit the impact of global warming. However, it is prudent to contemplate and plan for a warmer world and to consider 4°C and 5°C increase scenarios as well as 2°C.

Climate projections

Greenhouse gas emission scenarios are coupled with global climate models to estimate how climate may change in the future. The results of this modelling produce suites of climate projections for each emission scenario. Projections are usually presented as an average and a range of values for the short term (2020–30), medium term (2040–60) and long term (2070–2100), compared to conditions in the recent past. In planning for the future climate, it is important to understand the strengths and limitations of this modelling. The trajectory of future greenhouse gas emissions remains speculative, but for a given emission scenario there is good confidence in the associated temperature changes, reasonable confidence in rainfall changes and less confidence in how other climatic variables will change. The global climate models have a relatively coarse resolution, so they do not account very well for regional variability such as that induced by landforms or distance from the ocean. With this in mind, climate projections are not an absolute prediction of what will

happen, but rather broad pointers for what may happen, providing loose bounds in which to plan for future climate change.

The latest climate projections for WA show the average annual temperature increasing by 0.5–1.3°C by 2030 regardless of emission scenario, and by 1.1–2.7°C and 2.6–5.1°C by the end of the century under intermediate- and high-emission scenarios, respectively. Annual rainfall in the south-west is projected to decline by 6% by 2030 and 12% by the end of the century (median values) for an intermediate-emission scenario, and by 5% and 18% (median values), respectively, for a high-emission scenario. In the northern and central parts of the state, annual rainfall remains relatively unchanged. These changes will be superimposed on WA's already large natural climate variability. The intensity and duration of hot spells is expected to increase across WA. The incidence of frost in the south-west is expected increase in the short term then decline as global temperature increases. The frequency of rain events will decrease but storm intensity will increase. Similarly, the frequency of tropical cyclones may decline but they are likely to be more intense and travel further south. Consequently, wet years are likely to become less frequent and dry years (and drought) are likely to become more frequent. Evaporative demand will increase across the state.

Impacts of climate change

A warmer, drier and more variable climate presents significant environmental, social and economic risks to WA. The agricultural sector is particularly exposed to climate variability and climate change. To date, WA producers have proven to be innovative and resilient in dealing with a drying climate and declining terms of trade. However, future climate change means that producers will need to continue adapting to a suite of interacting climate change impacts. In addition to the climate changes outlined above, impacts include economic pressures and opportunities related to increasing human populations and changing human dietary preferences, increased input costs and energy prices, competing land-use pressures and policy-related economic pressures, such as measures to mitigate greenhouse gas emissions.

The impacts of climate change on agricultural productivity will vary regionally and by enterprise, with some regions and enterprises benefiting and some not. Changing rainfall, temperature, carbon dioxide (CO₂) and other climatic variables will affect average crop and pasture productivity, quality and nutrient cycling, pest and disease activity, livestock production and reproductive rates. It is likely that the interannual variability will increase across most of the state. Declining rainfall is likely to be the dominant (and predominately negative) influence. Increased CO₂ concentrations will improve the efficiency of plant water use and increased temperature could be beneficial or harmful depending on season and location. These changes will affect the profitability and financial risk associated with farming enterprises, particularly at the margins of currently suitable climatic zones.

In WA, improvements in technology, agronomy and cultivars have effectively increased the rainfall use efficiency of broadacre crops at a rate greater than rainfall decline. Projections of how climate change will affect future crop and pasture yields are constrained by the limitations of climate and crop models. Specifically, most crop

models do not capture technology and management improvements, extreme weather events and changes in pest and disease activity. However, some broad projections can still be made about the effects of climate change on agriculture in WA.

Broadacre crop yields will be most affected by changes in rainfall, and particularly the timing of rainfall, despite increased CO₂ improving plant water use efficiency.

Consequently, yields are likely to decline in the drier eastern and northern areas and remain largely unchanged or increase in wetter western and southern areas. The plant available water capacity of the soil will become increasingly important to growth, so yield declines are likely to be greater on clay soils compared to sands in eastern areas. Higher temperatures, and to a lesser extent declining rainfall, will hasten development times and reduce the flowering and grain-filling periods. The risks associated with climate variability will increase most in drier, marginal areas.

Forage production may be reduced by up to 10% over the agricultural areas and southern rangelands and by 10–20% over the rest of the state. Additionally, increased CO₂ concentrations could reduce pasture digestibility and protein content if forages with heat-tolerant C₄ metabolic pathways (tropical plant species) become more dominant. The decline in forage quality associated with increased growth of C₄ grass species may be offset by increased growth rates of leguminous species. The percentage decline in livestock productivity and profitability will be greater than the decline in pasture growth because of the need to retain minimum pasture cover to prevent soil erosion. Rainfall decline and increased interannual variability in pasture production is likely to place severe stress on rangeland ecosystems and grazing enterprises in southern WA.

Higher temperatures in winter and early spring could increase forage production, reduce livestock feed requirements (by lowering energy maintenance costs) and increase the survival rate of young animals or shorn sheep during cold and wet periods in the higher rainfall areas of the south-west. But in warmer areas of WA, and during the summer months, increased temperatures and heat stress could reduce forage growth, increase livestock maintenance requirements, reduce reproductive success and milk production, increase livestock water requirements and increase livestock exposure and susceptibility to parasites and disease.

For horticultural enterprises, increased temperatures could reduce chill accumulation (the time that air temperature is below 7.2°C which is critical to meeting the winter dormancy requirements of horticultural crops) by up to 100 hours. Increased average and maximum temperatures may also reduce fruit quality and cause burning of some leafy horticultural crops. The impact will vary by crop type, cultivar and location. For example, by 2030, the south-west will remain suited to grape production but banana production may be negatively affected at Kununurra and lettuce production may not be viable at Gingin. Decreased water availability is concerning to all producers but particularly for those irrigating their crops. Declining rainfall will have a profound effect on surface water and groundwater supplies. If rainfall declines by 14% in the south-west, it has been projected that streamflow will decline by 42% and groundwater recharge will decline by 53%.

In general, the impact of future climate change on natural resource condition is poorly understood; however, it is possible to identify some broad risks and trends. Declining rainfall associated with increased drought over the southern part of WA and increased rainfall intensity from tropical cyclones in the north will increase the risks of wind and water erosion, particularly if drier and more variable conditions caused a reduction in plant cover. Where climate change reduces plant growth, soil organic carbon could be expected to decline. While rates of secondary salinisation could be expected to decrease as rainfall decreases, secondary salinisation may be offset by more-intense storms causing episodic recharge events. Warmer and drier conditions will also continue to increase the number of fire risk days and potentially increase the intensity of wildfires.

Adapting to a changed climate

While the effects of climate change will vary regionally and by enterprise, all agricultural industries will need to deal with some level of climate change in the coming decades. Enterprises in currently marginal areas, such as the southern rangelands and the northern and eastern wheatbelt, are most at risk from climate change.

There are three broad levels of adaptation with increasing benefit but also increasing complexity, costs and risk:

- incremental, such as adjusting practices and technologies
- transitional, such as changing production systems
- transformative, such as relocating production.

Incremental changes are likely to continue to be effective in the medium term (2020–30) across most sectors and regions but transitional and transformative adaptations should also be considered for long-term planning or for medium-term planning in marginal areas.

Producers' terms of trade are critical in determining the future economic impacts of climate change and consequent adaptation strategies. If global agricultural yields decline while population increases, prices for agricultural commodities could be expected to rise, which may facilitate continued farming in marginal areas.

For broadacre agriculture in the wheatbelt, many of the incremental technological and management adaptations suggested are currently considered 'best practice'. However, there is considerable scope for increasing levels of adoption, particularly integrating adaptations into whole-of-farm systems. Wheat is likely to continue as the principal broadacre crop grown in WA but the future of dryland livestock farming is less certain. For most producers it is prudent to continue making incremental adaptations and to wait before making transformational changes. However, marginal eastern and northern areas are particularly vulnerable to the impacts of climate change so producers in these areas may need to consider more transformative changes sooner.

Changes in horticultural production associated with future climate change will depend on location and crop type. Water management will continue to be a primary concern. Less rainfall will decrease groundwater recharge and increase variability in dam storage volumes in the southern half of WA. Increased evaporation and increased climate variability may affect water availability elsewhere in the state. Adaptation will require improvements in irrigation practices, appropriate water policy and changes in crop variety and species to reflect water cost and availability. Increased temperatures will make matching of appropriate climatic areas to crop type increasingly important, particularly for long-lived perennial crops and those requiring a high degree of chilling. The area suitable for growing tropical and subtropical crops may expand but the area suitable for temperate crops may contract. Attracting investment in long-lived, climate-dependent agricultural assets, such as irrigation infrastructure, may become more difficult if not matched with investment in water efficient technologies.

Some pastoral areas are already under severe environmental and economic stress. If climate change reduces productivity and water availability, the imposition of additional stresses will mean that incremental adaptation will not be sufficient and that more transformative changes will be required. These adaptations may include increasing the efficiency of rangeland utilisation, changing to more heat-adapted livestock breeds or species and diversifying on-lease land uses.

The intensive livestock sectors are well-placed to deal with climate change, particularly where animals are confined and temperature extremes can be regulated. For these enterprises, and those such as feedlots and dairies where animals also spend some time outside, there are incremental adaptations available to deal with climate variability and change for the short to medium term. However, increasing energy efficiency or generating power on-farm will become increasingly important as energy costs and cooling requirements increase, as will improving water use efficiency, particularly irrigation efficiency.

While producers' ability to adapt to climate change in the long term is constrained by their adaptive capacity, most producers are likely to be able to continue adapting as long as they manage farm debt and have ongoing access to farm management and business education, and improved crop varieties and technologies. Adaptation strategies combining technological, behavioural, managerial and policy options will be required to offset the increasingly negative effects of climate change. Such strategies may actually improve enterprise profitability in the short term.

Across the agricultural sector, increasing enterprise resilience to climate variability is the most important climate issue in the short to medium term, with wider climate change effects broadly acknowledged as a long-term issue. To address these issues, there are some commonly identified research and development themes (in no particular order):

- climate projections at a local scale
- systems-based research to continue delivering incremental adaptations for short-to medium-term climate variability and change

- improved weather forecasting and a better understanding of the potential long-term impacts of climate projections on farming systems and related industries.

In conclusion, the agricultural sector needs to be informed about and prepared for climate change. For most producers the best advice is to continue to make incremental changes and wait and see what happens with future climate and technological developments before making transformational changes to their businesses.

1 Introduction

Climate change is affecting Australia's natural environment and the human systems it supports. Over the last 40 years, annual temperatures have increased by about 1°C over WA. Annual rainfall has increased in the northern and interior areas but has declined significantly along the west coast and in the south-west. There is overwhelming scientific consensus that human activities, particularly those increasing atmospheric greenhouse gas concentrations, are altering the global energy budget and contributing to these changes (Bindoff et al. 2013; Marvel & Bonfils 2013).

The scientific consensus indicates that unless global efforts to reduce the emission of greenhouse gases are rapidly and greatly increased, the effects of climate change will be profound. Average annual temperatures in WA could be 2–5°C warmer by 2070 and rainfall is likely to decline over much of the state (Commonwealth Scientific and Industrial Research Organisation [CSIRO] & Bureau of Meteorology [BoM] 2015). These changes will superimpose WA's already large natural climate variability, so wet years are likely to become less frequent while dry years (and drought) are likely to become more frequent (CSIRO & BoM 2014). A warmer, drier and more variable climate presents WA with significant environmental, social and economic risks. The Australian and Western Australian governments have recognised these risks and are working to mitigate them and increase resilience to climate change (Commonwealth of Australia 2010; Western Australian Government 2012).

The agricultural sector is particularly vulnerable to both climate variability and climate change. To date, WA producers have proven to be innovative and resilient in dealing with a drying climate and declining terms of trade. However, future climate change means producers must continue adapting to a suite of interacting climate change and socioeconomic impacts. These impacts include ecophysical changes such as higher temperatures, changes in rainfall distribution and amount and more frequent drought; economic pressures related to increasing human populations, changing human dietary preferences, increased input costs including increased energy prices; and policy-related economic pressures, such as land-use pressures and mitigating greenhouse gas emissions (Henry et al. 2012).

DAFWA is working to reduce the vulnerability of the agricultural sector to climate change and to increase its adaptive capacity. In 2010, DAFWA developed its 'Climate change response strategy' (Bennett 2010) to provide a strategic direction for climate change activities and to identify and prioritise actions to achieve over the following five years. Since the strategy was published, there have been considerable advances in the scientific understanding of climate change. This bulletin reviews the latest scientific information relating to climate change and agriculture in WA.

Reducing greenhouse gas emissions and maintaining the atmospheric carbon dioxide (CO₂) concentration below 450 parts per million (ppm) remains the best way to limit the impacts of global warming (Intergovernmental Panel on Climate Change [IPCC] 2014). In 2010, there was international agreement to limit global warming to less than 2°C by 2100, relative to the pre-industrial period, and to investigate lowering this limit to 1.5°C (United Nations Environment Programme [UNEP] 2014). This goal can only be achieved if CO₂ emissions are limited to 1000 gigatonnes (Gt)

to the end of this century. While this limit is technically feasible, it is likely to be exceeded unless the international community takes stronger action than currently pledged to limit emissions (Price Waterhouse Coopers 2012; UNEP 2014). A world that is more than 2°C warmer will pose many challenges for human society, so it is prudent to contemplate and plan for a warmer world and to consider 4°C and 5°C increase scenarios as well as 2°C.

2 Climate

2.1 The earth's radiation balance and global warming

Summary

- Over the last 260 years, the earth's land surface has warmed by about 1.5°C.
- The IPCC Fifth Assessment Report (AR5) concluded that it is very likely that more than half of the observed increase in global temperature is caused by human activities increasing greenhouse gas concentrations.
 - The atmospheric concentration of CO₂, which contributes 63% of the total atmospheric radiative forcing potential, has increased from 260ppm to 400ppm since the start of the industrial revolution, 260 years ago.
 - It may be 3–5 million years since CO₂ concentrations were this high.
 - CO₂ is accumulating in the atmosphere at an increasing rate despite international agreements to limit emissions.
- Long-term emission scenarios are coupled with various global climate models to simulate how increasing CO₂ concentrations will affect future climate.
 - Climate change projections are presented as probabilities and chances rather than just one outcome.
 - In the short term (2020–40), most of the variability in climate projections results from differences among global climate models rather than emission trajectories.
 - In the medium term (2050) and long term (2070–90), differences in emission trajectories become increasingly important in determining climate projections.
 - Global climate models do not deal well with phenomena that might induce abrupt changes in the climate system.
- Current CO₂ emissions are tracking among the higher emission scenarios.
- If current rates of CO₂ emissions continue, global temperatures may rise another 2.6–4.8°C by the end of this century.
- Warming in excess of 2°C is considered to present dangerous risks to the natural environment and human systems.

A number of natural processes operating over various timescales alter the earth's radiation balance and climate. The amount of solar energy reaching the earth changes as the energy output of the sun varies over an 11-year cycle, as the tilt of the earth's axis varies on a 41 000-year cycle and as the earth's orbit varies on a 100 000–400 000-year cycle (Jansen et al. 2007). Some solar energy is reflected back to space as short wave energy. The amount depends on the earth's albedo (reflectivity) which changes over periods of decades to millions of years. Albedo changes as continental drift alters the amount of energy intercepted by land or water, land cover changes (vegetation type or snow) and the amount of cloud cover or aerosols (small particles) in the atmosphere changes when events such as volcanic

eruptions emit ash and sulfur particles (Hay 1996; Jansen et al. 2007). The remaining energy heats the earth's atmosphere, land and oceans.

Heat and moisture move around the planet through oceanic and atmospheric circulation. This circulation changes over millions of years as continental drift opens and closes pathways to oceanic currents and uplifts land to produce barriers to wind (Hay 1996; Ramstein et al. 1997). Eventually, some energy radiates back out to space as long wave energy (heat), with the amount determined by the concentration of greenhouse gases in the atmosphere. Possible sources of greenhouse gases responsible for past climate changes include methane from the breakdown of methane clathrates — a compound of methane enclosed within a cage of water molecules to forming an icy solid — on the sea floor, and CO₂ from volcanic activity or oxidation of sediments that were rich in organic matter. Solar variability and volcanic activity are likely to be the leading reasons for climate variations during the millennium before the industrial revolution (Jansen et al. 2007).

Since the start of the industrial revolution 260 years ago, the earth's land surface has warmed by about 1.5°C (Figure 2.1) and is now hotter than at any time over the last 1400 years (PAGES 2k Consortium 2013). This global warming is attributed to increased radiative forcing as human activities have increased the concentration of the greenhouse gases CO₂, methane, nitrous oxide, ozone and halocarbons in the atmosphere (Figure 2.2) (Myhre et al. 2013; Hegerl et al. 2007; Price Waterhouse Coopers 2012; World Bank 2012; Cook et al. 2013).

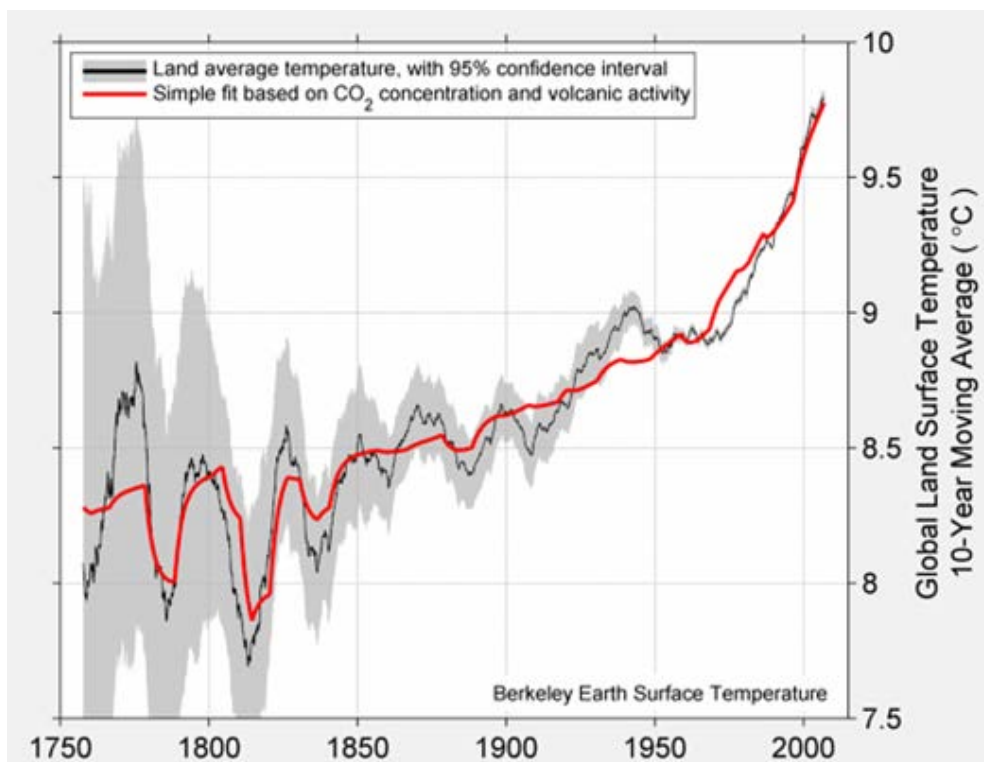


Figure 2.1 Global land surface temperature since 1750. The shaded area indicates statistical and spatial sampling errors. The wide, red, solid line shows temperature estimates from a simple model accounting for volcanic eruptions and atmospheric carbon dioxide concentration (Rohde et al. 2013)

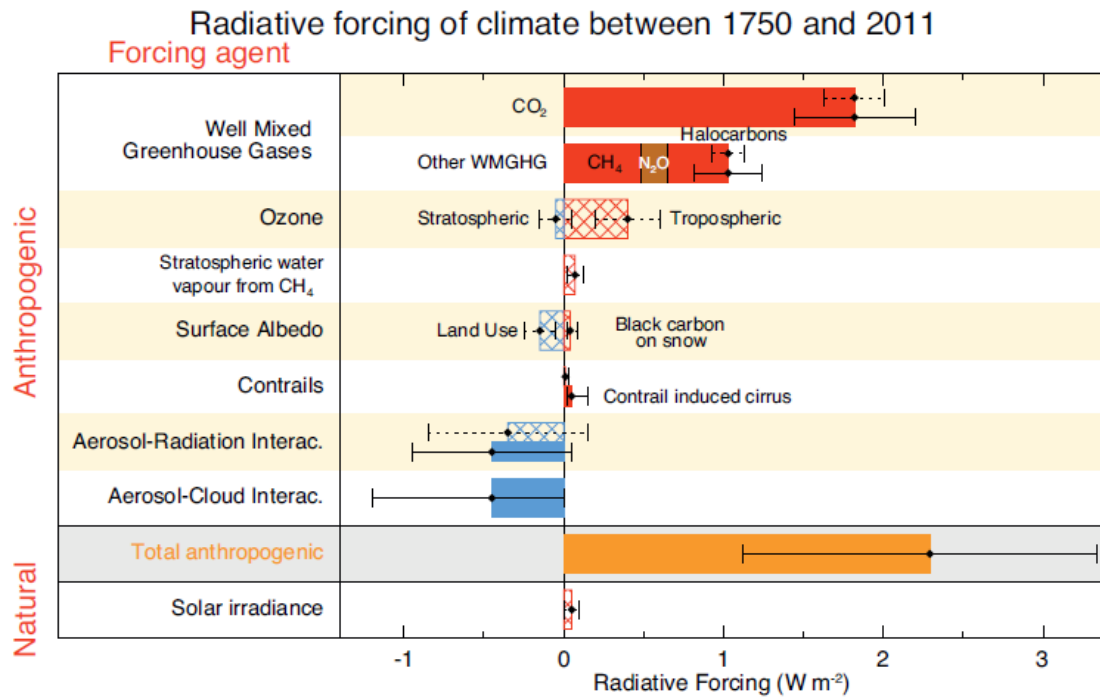


Figure 2.2 Principal components of the radiative forcing (solid shading) and effective radiative forcing (hatched shading) of climate change. CO₂ = carbon dioxide, CH₄ = methane, N₂O = nitrous oxide. Error bars show 95% confidence range (Myhre et al. 2013)

The IPCC Fifth Assessment Report (IPCC AR5; Prather et al. 2013) concluded that it is 'now virtually certain' (99–100% probability) that internal variability alone cannot account for the observed global warming since 1951. Also, it is 'very likely' (90–100% probability) that more than half of the observed increase in global temperature is caused by human activities increasing greenhouse gas concentrations (Bindoff et al. 2013).

Carbon dioxide contributes 63% of the total atmospheric radiative forcing potential (Solomon et al. 2007) and is closely correlated with increasing global temperature (Figure 2.1) (Rohde et al. 2013). Over the last 260 years, the concentration of atmospheric CO₂ has increased from about 278ppm to reach 400ppm in May 2013 (Freedman 2013). This may be the highest CO₂ concentration since the middle Miocene (3–5 million years ago) when global temperatures were 3–6°C warmer and sea level was 25–40m higher (Tripathi et al. 2009; Schneider & Schneider 2010).

The rate at which CO₂ is being added to the atmosphere has increased from 1–1.9% annually in the 1980s and 1990s to 3.1% annually since 2000 (Figure 2.3a) (Peters et al. 2013; Le Quéré et al. 2014). The rate of increase in radiative forcing over the last 100 years from CO₂, methane, and nitrous oxide combined is very likely to be unprecedented in the last 16 000 years (Jansen et al. 2007).

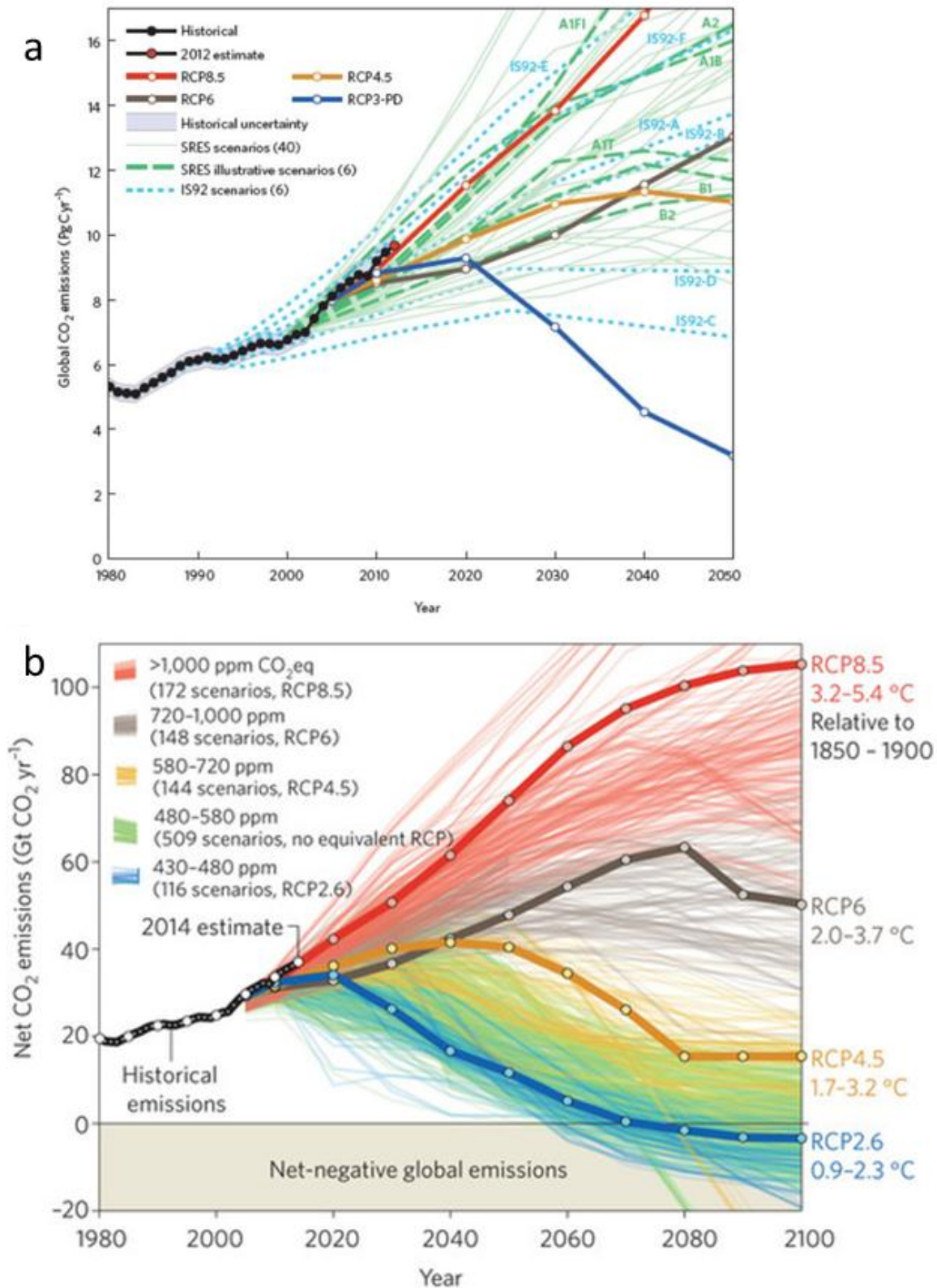


Figure 2.3 Historical emissions and estimated emissions for various scenarios: (a) IPCC Scenarios 1992 (IS92), *Special report on emissions scenarios* (SRES) and representative concentration pathways (RCPs); and (b) RCP scenarios showing estimated CO₂ atmospheric concentration and increase in global temperature by 2100. 1ppm = 7.81 gigatonnes (Gt) of CO₂ (Peters et al. 2013; Fuss et al. 2014)

About 60% of the CO₂ reaching the atmosphere is removed within 100 years, with 20–35% remaining in the atmosphere for 2 000–20 000 years (Mackey et al. 2013). The residence time of CO₂ is far longer than methane and nitrous oxide, which remain in the atmosphere for about 10 and 100 years, respectively. So, while 100 years is a commonly used term to express greenhouse gas warming potential, current CO₂ emissions will actually continue to affect global climate for thousands of years to come.

The rate of global atmospheric warming has been variable. This is a consequence of external (the factors driving climate change described in the first paragraphs of this section) and internal (for example, the El Niño–Southern Oscillation) sources of climate variability (Guemas et al. 2013; Smith et al. 2015). Atmospheric temperatures increased rapidly in the 1920s to 1940s, cooled slightly in the 1940s and 1960s and increased rapidly again in the 1970s to 1990s. The rate of temperature increase has slowed substantially over the past 15 years (Guemas et al. 2013; Smith et al. 2015). Solar radiation peaked in the 1930s then substantially decreased from the 1940s to 1970s, and it has remained relatively constant since (Wang & Dickinson 2013).

While the rate of atmospheric warming has declined recently, the total amount of heat energy stored in the earth's surface systems has continued to increase, with most of the extra heat being stored in the oceans (Figure 2.4) (Nuccitelli et al. 2012; Guemas et al. 2013; Trenberth & Fasullo 2013). Recent studies have shown strong links between increased concentrations of greenhouse gases from human activities and record high temperatures in Australia during 2013 (Arblaster et al. 2014; King et al. 2014; Lewis & Karoly 2014; Perkins et al. 2014).

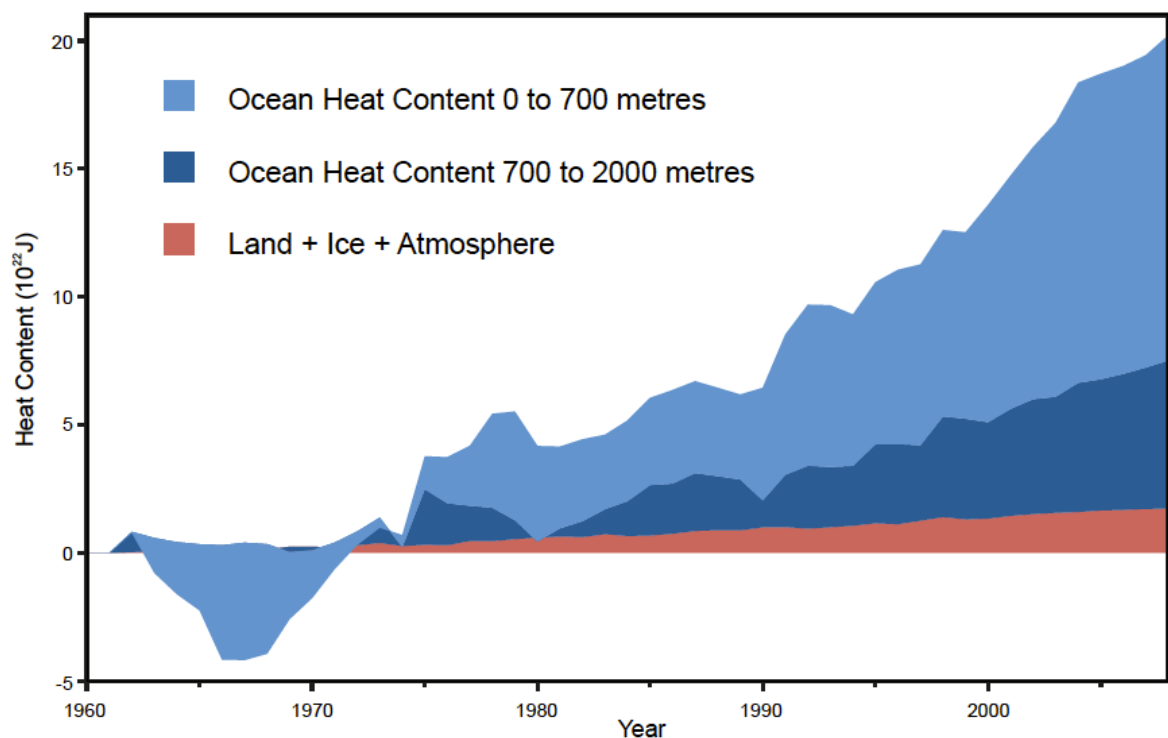


Figure 2.4 Global heat content of land, atmosphere, ice and oceans from 1960 to 2012 (Nuccitelli et al. 2012)

2.2 Modelling future climate

To simulate how increasing atmospheric CO₂ concentrations will affect future climate, long-term emission scenarios are used together with various climate models. These emission scenarios are designed to account for a wide range of demographic, economic, and technological drivers of greenhouse gas and sulfur emissions over the years to 2100 (Table 2.1) (Nakicenovic et al. 2000). The most commonly used emission scenarios are those detailed in the IPCC's *Special report on emissions scenarios* (SRES) and the representative concentration pathways (RCPs) used in the IPCC AR5 (Prather et al. 2013). The RCP scenarios account for international commitments to reduce greenhouse gas emissions.

Global climate models are the primary tool for investigating and testing how the atmosphere is likely to respond to changes in greenhouse gases. They simulate the physical relationships behind the major weather and climate features and how they interact with the land and the ocean. The models allow the impacts of changes in major radiative drivers (Figure 2.2) to be tested. Modelling studies of climate change are usually run as ensembles of multimodel simulations. Ensembles help deal with uncertainties arising from the internal variability of the oceans and atmosphere, and from limitations in the models' ability to simulate all processes in sufficient detail. Consequently, climate change projections are not just one simulation of the future, but of many possible futures. As there are also many possible trajectories for emissions of greenhouse gases (Figure 2.3), future climate projections are presented as probabilities and chances rather than just one outcome (Appendix A).

IPCC AR5 uses the RCP emission trajectories and the Coupled Model Intercomparison Project Phase 5 Model Suite (CMIP5) (Stocker et al. 2013). CMIP5 uses more than twice as many models, many more experiments and treats a larger number of forcing agents more completely than the 2007 IPCC modelling. However, most of the differences in climate projections reported in IPCC AR5 compared to previous reports stem from the differences in the emission scenarios rather than outputs from the global climate models. As the RCP scenarios and CMIP5 global climate models are recent developments, they are only just beginning to be used in Australian climate studies.

Most of the variability in short-term (2020–30) climate simulations results from differences among global climate models rather than emission trajectories. However, differences in emission trajectories become increasingly important in determining medium-term (2050) and long-term (2070) climate outcomes (CSIRO & BoM 2015).

Global climate model suites do not deal well with phenomena that might induce abrupt changes in the climate system or some of its components. Such phenomena are considered to exhibit threshold behaviour; that is, they may have a tipping point beyond which abrupt and large changes in behaviour are triggered. These include the strength of the Atlantic Meridional Overturning Circulation, methane clathrate release, tropical and boreal forest dieback, disappearance of summer sea ice in the Arctic Ocean, long-term drought and monsoonal circulation (Stocker et al. 2013).

Table 2.1 Projected atmospheric CO₂ concentrations and global surface temperature change (T) for SRES illustrative emission scenarios and representative concentration pathways (RCPs) in 2030, 2050 and 2090. Temperature values are relative to conditions in 1990 for SRES trajectories and relative to average conditions between 1986 and 2005 for RCP trajectories (Nakicenovic et al. 2000; Solomon et al. 2007; Collins et al. 2013; Prather et al. 2013)

Emission trajectory	Scenario	CO ₂ (ppm) 2030	CO ₂ (ppm) 2050	CO ₂ (ppm) 2090	T (°C) 2030	T (°C) 2050	T (°C) 2090
A1F1	Rapid economic growth, global population peaks in 2050, rapid introduction of new technologies, intensive use of fossil fuels.	455	567	885	0.9 *	1.9 *	4.5 *
A1T	Rapid economic growth, global population peaks in 2050, rapid introduction of new technologies, increasing use of renewable energy.	440	501	577	1.0 *	1.8 *	2.5 *
A1B	Rapid economic growth, global population peaks in 2050, rapid introduction of new technologies, mixed energy sources.	454	532	685	0.9 *	1.6 *	3.0 *
A2	High global population growth, slow economic development, disparate living standards.	448	527	762	0.7 *	1.4 *	3.8 *
B1	Global population peaks in 2050, convergent living standards, rapid move to service and information economies.	434	628	542	0.8 *	1.2 *	2.0 *
B2	Intermediate population and economic growth, solutions based around economic and environmental sustainability.	429	478	589	0.9 *	1.4 *	2.7 *
RCP 2.6	Emissions rapidly decline to zero and sequestration technologies begin to reduce atmospheric CO ₂ by 2050.	431	443	426	0.7 [†] (0.5–1.2)	0.9 [†] (0.5–1.7)	0.9 [†] (0.2–1.8)
RCP 4.5	CO ₂ concentrations are slightly above those of RCP 6.0 until after mid-century, but emissions peak around 2040	435	487	534	0.8 [†] (0.6–1.2)	1.2 [†] (0.8–2.0)	1.7 [†] (1.1–2.6)
RCP 6.0	Gradual reduction in emissions, atmospheric CO ₂ concentration continues to increase then stabilises around 2100.	429	478	636	0.7 [†] (0.4–1.2)	1.2 [†] (0.7–1.8)	2.0 [†] (1.5–3.2)
RCP 8.5	Emissions and atmospheric CO ₂ concentration continue to increase at current rates.	449	541	845	0.9 [†] (0.7–1.4)	1.7 [†] (1.2–2.4)	3.6 [†] (2.6–4.8)

* Average temperature change; [†] Median temperature change, values in brackets are 5th and 95th percentiles.

While there is information about potential consequences of some abrupt changes, there is low confidence and little consensus on the likelihood of such events over the 21st century (Stocker et al. 2013).

The relatively coarse spatial resolution of global climate models can also lead to inaccurate projections, particularly in coastal and mountainous areas (CSIRO & BoM 2015). This source of error can be reduced by downscaling using local climate data.

To account for this variability (or uncertainty) among models, it is usual to present the results from a suite of models, including the range and the median projection along with a rating of the confidence in the projection (Appendix A). A comprehensive discussion of the sources of uncertainty around climate modelling and how data should be assessed and used is presented in CSIRO and BoM (2007, 2015).

Current CO₂ emissions are tracking among the higher emission scenarios (Figure 2.3). In 2013, the United States Energy Information Administration (EIA 2013) predicted that global energy use will increase by 56% between 2010 and 2040 with fossil fuels still contributing 80% of total energy supply in 2040. If these rates of CO₂ emission continue, global temperatures may rise by another 2.6–4.8°C by the end of this century (Table 2.1; Bodman et al. 2013; International Energy Agency [IEA] 2013; Hare et al. 2013). Global warming of this magnitude will profoundly affect ecosystems and society (Figure 2.5). Warming in excess of 2°C is considered to present dangerous risks to the natural environment and the human systems it supports, including food, water, infrastructure and health (Henson 2011, World Bank 2012; IEA 2013).

In WA, average annual temperature could be 2.6–5.1°C warmer by 2090 and rainfall is likely to decline by 5–37% in the south-west but remain relatively unchanged for the rest of the state (Hope et al. 2015; Moise et al. 2015; Watterson et al. 2015). These changes will superimpose WA's already large natural climate variability and so wet years are likely to become less frequent while dry years (and drought) will become more frequent (CSIRO & BoM 2014; Steffen et al. 2014). If WA becomes warmer and drier with a more variable climate, the state will need to deal with the associated environmental, social and economic risks.

The worst effects of climate change can be avoided if greenhouse gas emissions are significantly reduced. However, reducing emissions will require high levels of technological, social and political innovation and over time, a move from net emission reduction to net sequestration (Figure 2.3b; World Bank 2012; IEA 2013; Peters et al. 2013; Fuss et al. 2014; Hare et al. 2014). Afforestation and bioenergy with carbon capture and storage are considered potentially important mitigation options for achieving net sequestration (Fuss et al. 2014). These technologies present some opportunities for the agricultural sector.

At the 2015 International Climate Change Conference in Paris, national governments recognised the need to hold "...the increase in the global average temperature to well below 2 °C above preindustrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above preindustrial levels,..." (Framework Convention on Climate Change 2015). However, the emission pledges made at that meeting still place the world on a median trajectory for global warming of 3–3.5°C by 2100 (UNEP 2015).

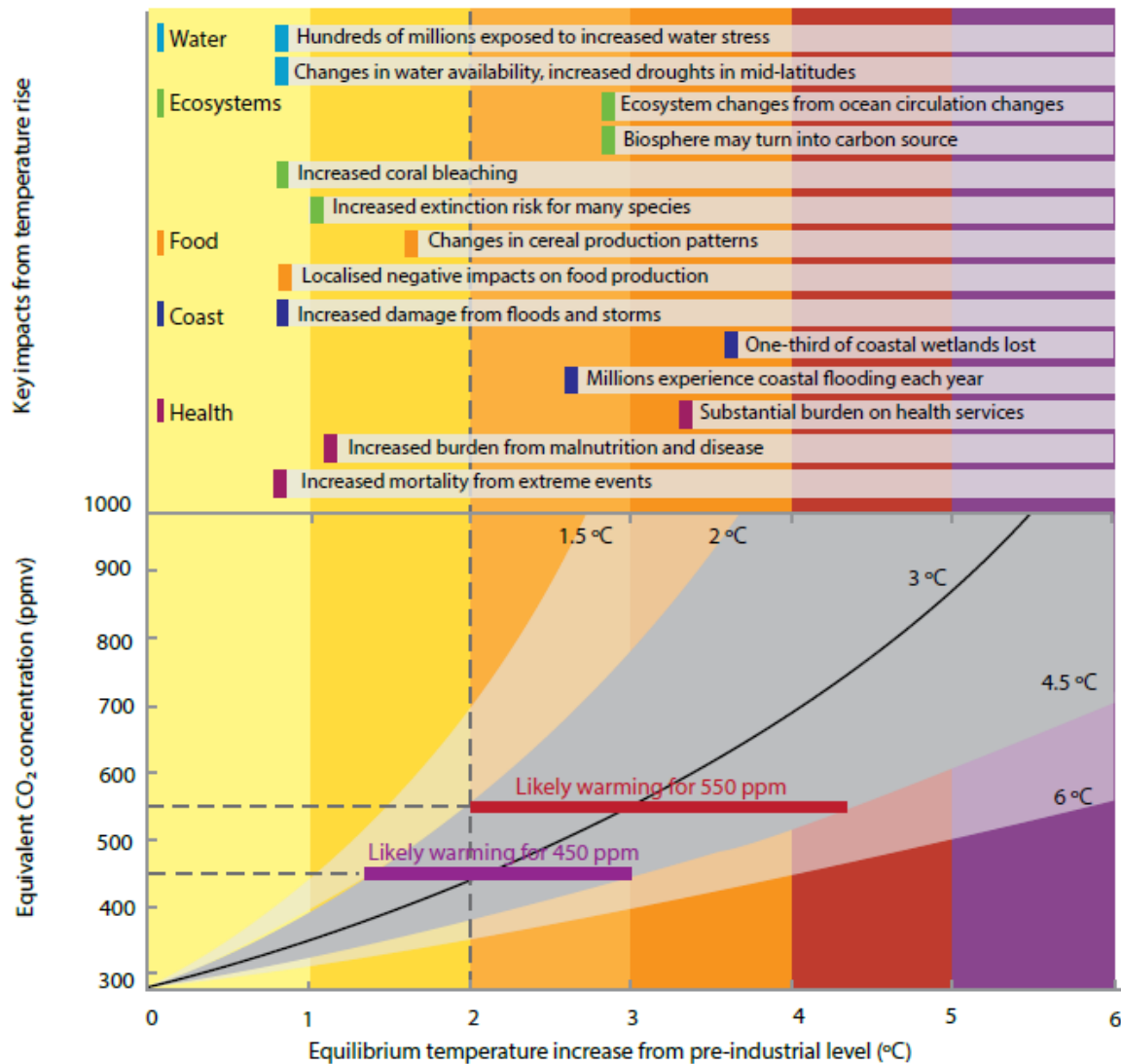


Figure 2.5 Relationship between atmospheric CO₂ concentration and global land temperature and likely impacts (Knutti & Hegerl 2008)

The longer it takes global emission rates to decrease, the more difficult it becomes to keep global warming below 2°C (Price Waterhouse Coopers 2012; World Bank 2012; Peters et al. 2013). Given current emission levels, the scope of current international emission pledges and the uncertainty that those pledges will be met, it is prudent to contemplate and plan for a warmer world with 4°C and 5°C increase scenarios as well as 2°C.

In planning for our future climate, it is important to understand the strengths and limitations of climate modelling. The trajectory of greenhouse gas emissions in the future remains speculative, but for a given emission scenario there is good confidence in the associated temperature changes, reasonable confidence in rainfall changes but less confidence in how other climatic variables will change. The global climate models have a relatively coarse resolution, so they do not account well for regional variability, such as topography or distance from the ocean. With this in mind, climate projections are not an absolute prediction of what will happen, but rather broad pointers for what may happen, providing loose bounds in which to plan for future climate change.

2.3 Climate drivers in Western Australia

WA's climate varies from tropical in the north to desert in the interior and to Mediterranean in the south-west (Figure 2.6). Rainfall in the south-west is winter-dominant and increases with proximity to the coast. Rainfall is summer-dominant in the central, interior and northern areas and increases at lower latitudes, becoming monsoonal in the far north.

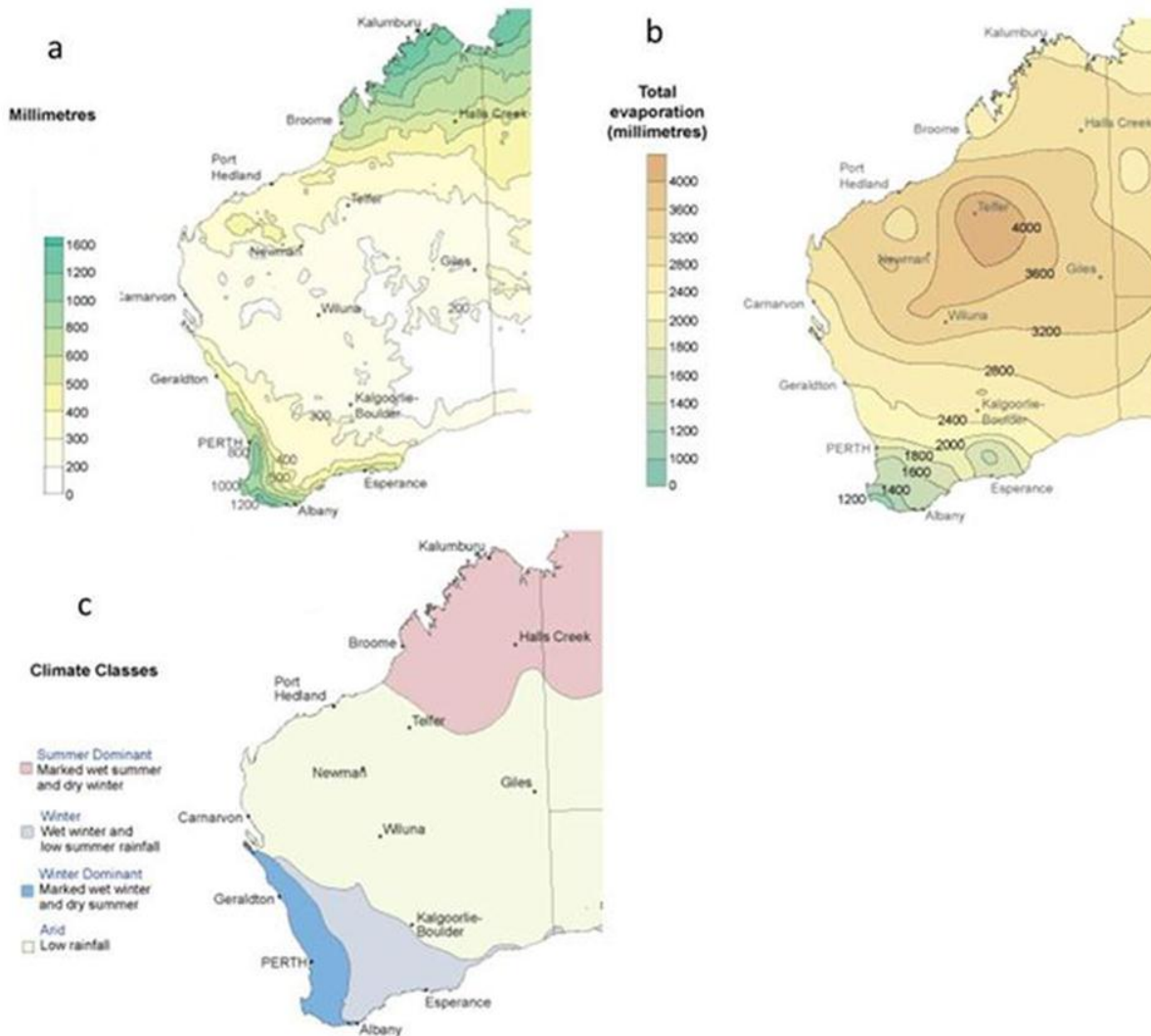


Figure 2.6 (a) Average annual rainfall; (b) average annual pan evaporation; and (c) seasonal climate classes for WA (BoM 2014)

The drivers for WA's weather operate from the level of global circulation, such as the subtropical ridge and the monsoon, to a regional scale, such as frontal systems and the west coast trough (Figure 2.7). Analysis of tree rings dating back 350 years show alternating 20–30-year periods of relatively dry weather and 15-year periods of above-average rainfall that reflect low-level variation in the El Niño–Southern Oscillation (Cullen & Grierson 2009).

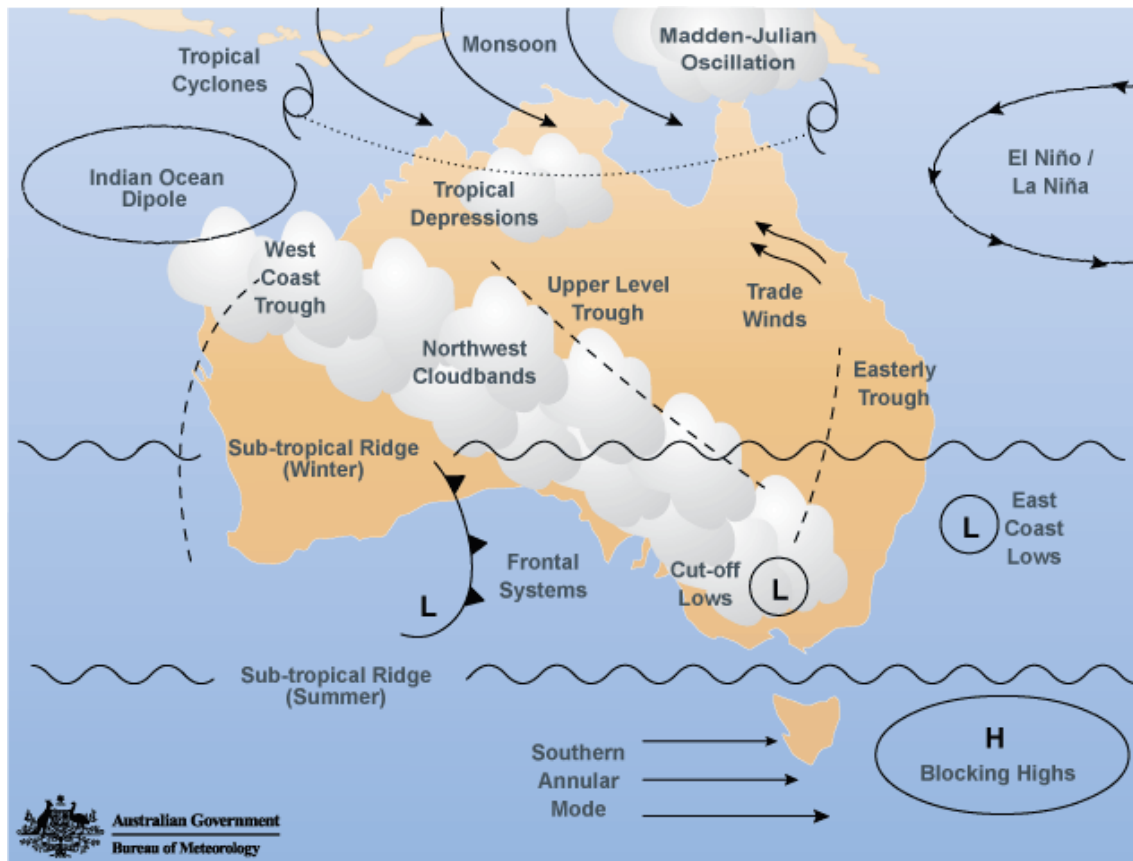


Figure 2.7 Major weather and climate drivers across Australia (BoM 2016)

The subtropical ridge is an extensive area of high pressure that encircles the globe at the middle latitudes (BoM 2010). The position of the ridge varies with the seasons, allowing cold fronts to pass over southern WA in the winter, but pushing them south of the state in summer. Conditions along the ridge tend to be stable and dry. Consequently, the south-west of WA is characterised by dry, hot summers and winter weather is characterised by moist, unstable winds associated with frontal systems (BoM 2010). Eighty per cent of annual rainfall in the south-west falls between the cooler months of April and October.

The movement of the ridge also allows the monsoon to develop in the far north during summer (BoM 2010). The monsoon can be in either an 'active phase', characterised by moderate wind and rain, or an 'inactive phase', characterised by lighter wind and less rain. During the monsoon season, systems such as tropical cyclones and tropical depressions can affect northern and central parts of WA and occasionally southern WA.

The Indian Ocean Dipole — the difference in sea temperatures in the western and eastern Indian Ocean — and the El Niño–Southern Oscillation index — quantified as differences in atmospheric pressure across the Pacific Ocean — act individually and interact to affect tropical cyclone activity and rainfall across northern Australia (Charles et al. 2013).

North-west cloud bands can bring sustained rainfall when a trough of low pressure occurs in the upper levels of the atmosphere, or warm, moist, tropical air originating over the Indian Ocean moves towards the pole (generally south-easterly) (BoM 2010).

2.4 Current and projected climate and water resources in Western Australia

Summary

- WA's climate has changed over the last century, particularly over the last 50 years:
 - Average temperature has increased by about 1°C.
 - Rainfall has increased slightly over the north and interior but declined along the west coast. Rainfall has declined by about 20% over the far south-west.
 - Drier conditions have increased frost risk in central and eastern areas of the wheatbelt.
 - Fire risk has increased.
- These changes are greater than what would be expected from purely natural climate variability and are consistent with global warming.
- Climate projections suggest:
 - Average temperatures will be 0.5–1.3°C higher by 2030, regardless of emission scenario, and 1.1–2.7°C and 2.6–5.1°C higher at the end of the century under intermediate- and high-emission scenarios, respectively, compared to average conditions from 1986 to 2005.
 - Frost incidence is expected to increase in the short term before declining as temperatures increase.
 - The intensity and duration of hot spells are expected to increase.
 - Annual rainfall in the south-west will be 5–6% less by 2030 and 1–15% and 5–35% less by 2090 for intermediate- and high-emission scenarios, respectively, compared to average conditions from 1986 to 2005.
 - Annual rainfall will remain relatively unchanged in northern and central regions.
 - The number of dry days and agricultural drought will increase across most of WA, particularly in the south-west.
 - The frequency of rain events will decrease but storm intensity will increase.
 - Tropical cyclone frequency may decline but tropical cyclones may increase in intensity and travel further south.
 - Evaporative demand will increase.
 - Declining rainfall and increasing evaporative demand will decrease groundwater recharge and surface water flow, with the greatest reductions in the south-west.
 - Changes in average wind speed are likely to be small.
 - Fire risk will increase.

As global temperatures increase, the hydrological cycle intensifies and atmospheric circulation patterns change, the tropical belt widens and storm tracks and subtropical dry zones move towards the poles (Marvel & Bonfils 2013). These changes are affecting rainfall in WA in ways that are greater than what would be expected purely from interannual and interdecadal (for example, the El Niño–Southern Oscillation) modes of natural variability (Marvel & Bonfils 2013).

This review presents information relating to current and projected climate trends on a statewide and regional basis. For information about trends at specific locations of interest to the horticultural industry see Ward (2009) and Reid (2010), and for wheatbelt districts see Carmody (2010a, 2010b) and Carmody et al. (2010a, 2010b). The following sections describe changes in WA's climate in recent decades and changes projected to the end of the century. Much of this information summarises the findings of the Indian Ocean Climate Initiative Stage 3 using Phase 3 of the Coupled Model Intercomparison Project (CMIP3) global climate models (Bates et al. 2012), and more recently, analyses by the CSIRO and BoM using the latest CMIP5 global climate models (CSIRO & BoM 2015).

The latest Australian analysis by CSIRO and BoM (2015) was regionally based, with the regions largely defined by natural resource management boundaries. In this analysis, their Southwestern Flatlands region broadly aligns with the south-west land division but their Rangeland Region covers the entire arid interior of Australia and their Monsoonal North Region encompasses the Kimberley and northern parts of the Northern Territory and Queensland.

Table 2.2 shows future climate projections for various WA locations derived from three CMIP5 global climate models and indicate how projections vary between global climate models. Although the variability in projections can be considerable, there are some general trends. For example, temperature projections at all stations show an increasing trend over time and the increase is greater for the higher emission scenario. However, rainfall projections are more variable than temperature and are positive or negative in the north of the state but become increasingly negative for southern locations and over time.

2.4.1 Average temperature

Current trends

Between 1910 and 2013, average annual temperature increased by 0.9°C in the Kimberley, 1.1°C in the south-west and 1.0°C in the interior (Hope et al. 2015; Moise et al. 2015; Watterson et al. 2015). While average annual temperatures have increased, changes in seasonal average temperatures have been mixed (Figure 2.8). Summer cooling has occurred over northern WA. The Mid West and Perth areas have warmed and summer cooling has occurred along the south coast. These changes are likely to reflect increasing summer rainfall over northern WA giving a cooling effect, stronger high pressure systems over southern WA giving a heating effect, and proximity to the coast moderating temperatures on the south coast (Bates et al. 2012).

Table 2.2 Annual values of maximum temperature, rainfall and the number of severe fire danger days (SEV — the number of days per year when the Forest Fire Danger Index is greater than 50) for the historical 1985–2005 (1995) climate, and the per cent difference from the baseline values under projected climate for 2020–39 (2030) and 2080–99 (2090) for various WA towns. Values are the range derived from three CMIP5 global climate models for RCP 4.5 and RCP 8.5 emission scenarios (Hope et al. 2015; Moise et al. 2015; Watterson et al. 2015)

Variable	Town	1995	2030 RCP 4.5	2030 RCP 8.5	2090 RCP 4.5	2090 RCP 8.5
Temperature (°C)	Broome	32.2	3 to 4	3 to 4	6 to 7	9 to 12
	Port Hedland	33.4	3 to 6	3 to 6	6 to 8	9 to 16
	Carnarvon	27.5	4 to 6	4 to 6	7 to 11	11 to 18
	Meekatharra	28.9	4 to 6	4 to 6	7 to 10	10 to 17
	Geraldton	26.9	4 to 5	4 to 5	6 to 11	13 to 18
	Perth	24.6	5 to 5	4 to 5	7 to 11	13 to 19
	Kalgoorlie	25.2	4 to 7	5 to 6	8 to 12	12 to 20
	Albany	20.1	6 to 6	5 to 7	8 to 14	16 to 23
	Esperance	21.7	6 to 6	4 to 6	7 to 13	15 to 21
Rainfall (mm)	Broome	600	-6 to 9	0 to 16	8 to 15	-5 to 16
	Port Hedland	314	-37 to 1	-29 to 3	-17 to 1	-39 to 7
	Carnarvon	228	-54 to -7	-39 to -9	-39 to -6	-64 to 5
	Meekatharra	236	-46 to 7	-24 to 7	-20 to 9	-47 to 24
	Geraldton	452	-36 to -9	-29 to -11	-39 to -9	-56 to -24
	Perth	784	-35 to -8	-29 to -11	-40 to -10	-57 to -25
	Kalgoorlie	265	-49 to 5	-28 to 5	-23 to 8	-53 to 24
	Albany	795	-35 to -1	-26 to -4	-36 to -4	-55 to -19
	Esperance	623	-34 to -1	-26 to -5	-36 to -5	-55 to -19
SEV	Broome	1.5	0 to 60	13 to 40	47 to 73	100 to 287
	Port Hedland	10.7	2 to 151	15 to 98	35 to 89	27 to 331
	Carnarvon	0.6	33 to 367	33 to 167	67 to 150	50 to 517
	Meekatharra	23.8	15 to 106	18 to 58	33 to 64	36 to 159
	Geraldton	8.1	3 to 51	5 to 11	12 to 37	42 to 93
	Perth	2.5	4 to 52	16 to 20	16 to 72	88 to 172
	Kalgoorlie	10.7	7 to 95	11 to 58	22 to 48	22 to 142
	Albany	0.3	0 to 67	0 to 33	0 to 67	33 to 133
	Esperance	1.4	14 to 64	29 to 29	36 to 64	64 to 164

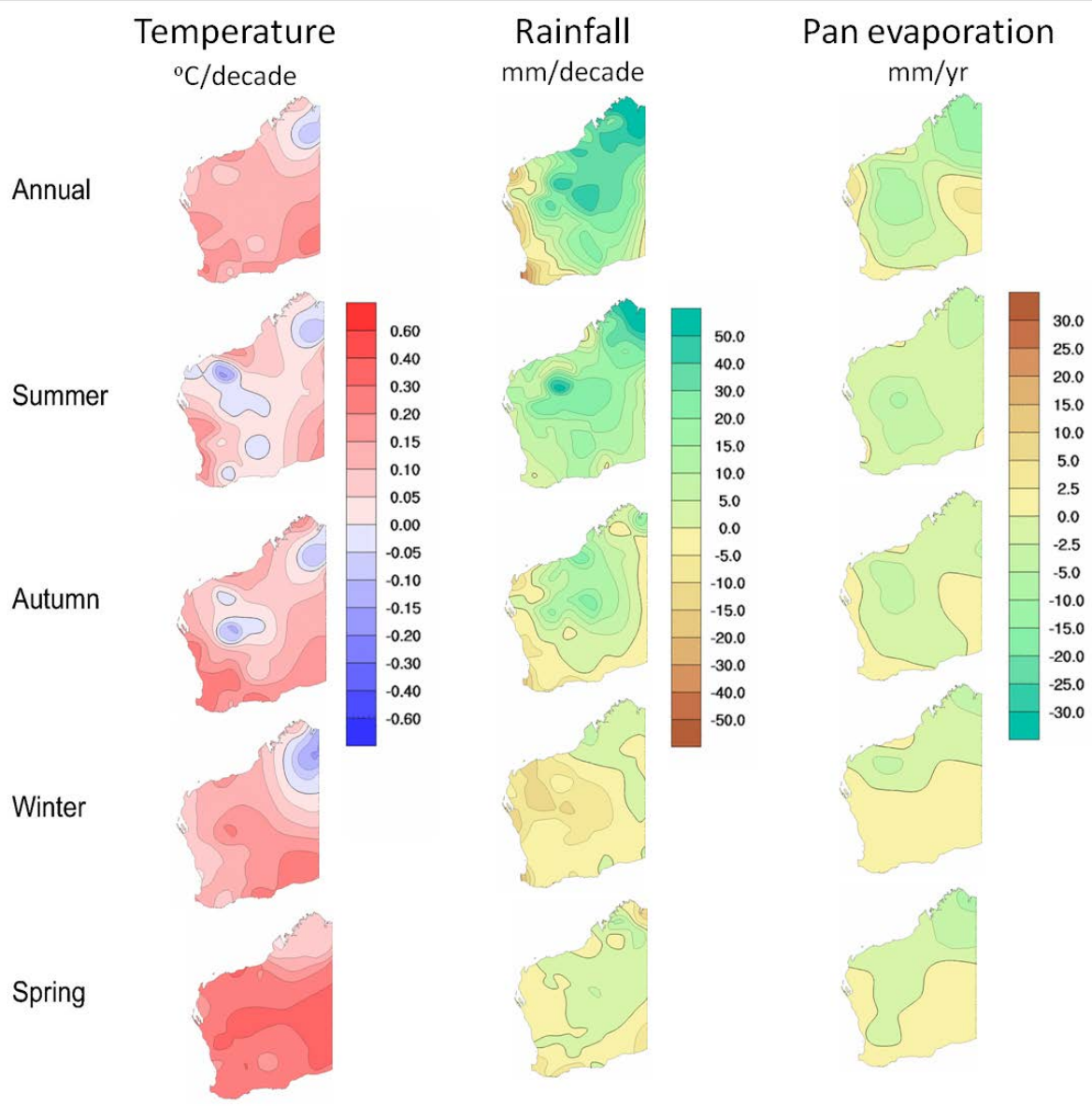


Figure 2.8 Historic (1970–2012) trends in temperature, rainfall and pan evaporation for WA (BoM viewed July 2013

<http://www.bom.gov.au/climate/change/index.shtml#tabs=Tracker&tracker=timeseries>)

Future projections

There is very high confidence (Appendix A) in projections that average, maximum and minimum temperatures will continue to increase to the end of the century (CSIRO & BoM 2015). Figure 2.9a shows a marked southern movement in isotherms between 2015 and 2090. Temperatures increase for all emission scenarios but are greater for higher emission scenarios with a high level of agreement between global climate models (CSIRO & BoM 2015).

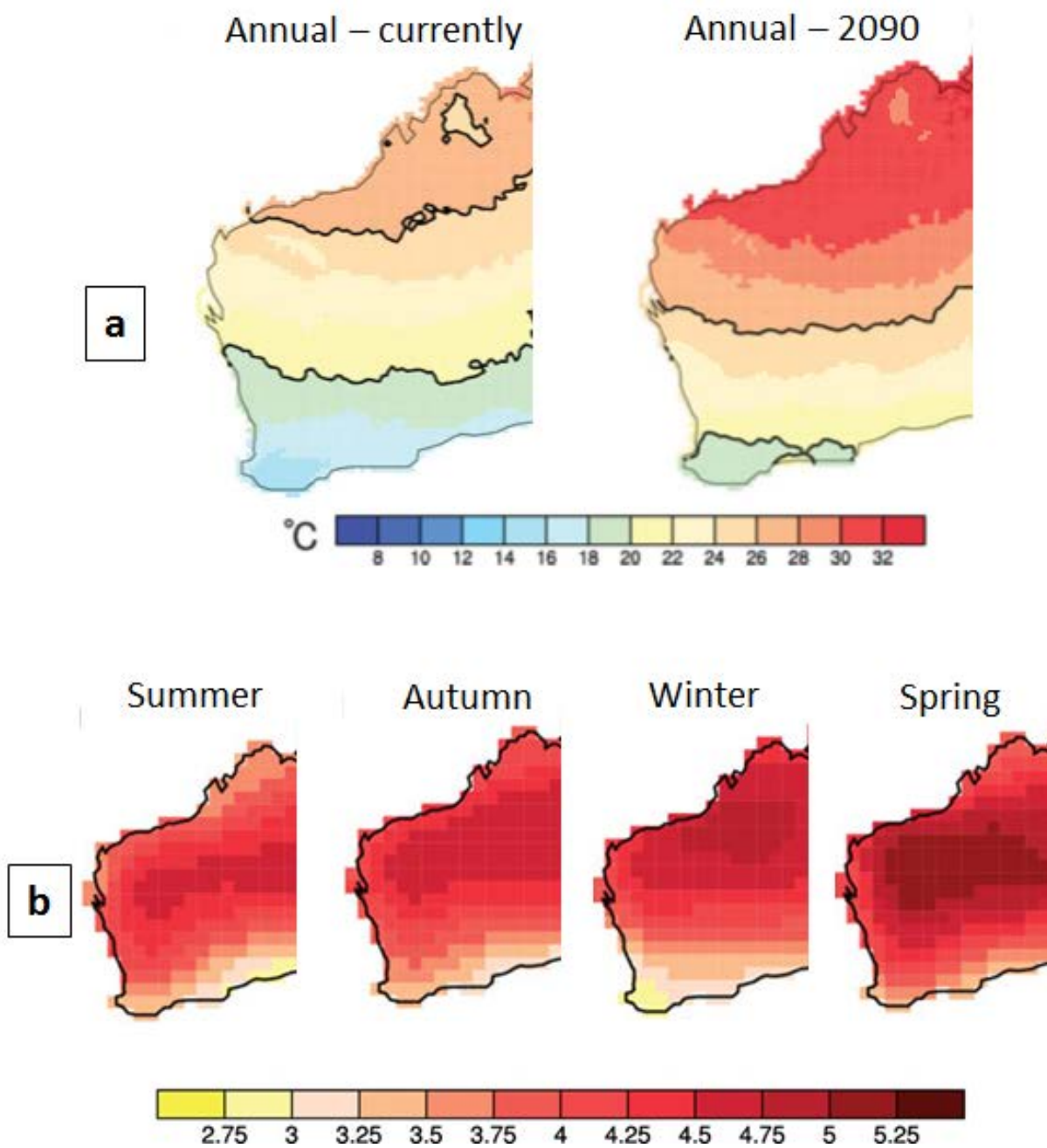


Figure 2.9 (a) Annual average temperature ($^{\circ}\text{C}$) for present climate (2015) and projected climate for 2090 under RCP 8.5; and (b) projected change in seasonal average temperature in 2090 under RCP 8.5 (CSIRO & BoM 2015)

In the south-west of the state, average annual temperature is projected to increase by $0.5\text{--}1.2^{\circ}\text{C}$ by 2030 under intermediate- and high-emissions scenarios (RCP 4.5 and RCP 8.5, respectively) compared to average conditions from 1986 to 2005 (Appendix 1 in Hope et al. 2015). By 2090, average annual temperature is projected to increase by $1.1\text{--}2.1^{\circ}\text{C}$ and $2.6\text{--}4.2^{\circ}\text{C}$ under RCP 4.5 and RCP 8.5, respectively (Figure 2.9b, Appendix B). Average maximum and minimum temperatures are projected to increase by similar amounts. There is little seasonal variation in projected temperature increase (Appendix B).

Average annual temperature in the Monsoonal North of Australia (a natural resource management region that includes the Kimberley) is projected to increase by 0.6–1.3°C by 2030 under intermediate- and high-emission scenarios (RCP 4.5 and RCP 8.5, respectively) compared to average conditions from 1986 to 2005 (Appendix B; Moise et al. 2015). By 2090, average annual temperature is projected to increase by 1.3–2.7°C and 2.8–5.1°C under RCP 4.5 and RCP 8.5, respectively (Figure 2.9b, Appendix B). Average maximum and minimum temperatures are projected to increase by similar amounts as the average daily mean temperature. There is little seasonal variation in projected temperature increases (Appendix B). Projected temperatures using CMIP3 modelling for just the Kimberley are slightly less, with the annual average maximum daily temperatures projected to increase by 1.8–2.7°C by 2050 and 3.6–4.6°C by 2090. Annual average daily minimum temperatures are projected to increase by 2.0–2.7°C and 4.2–4.9°C by 2050 and 2090 respectively (Bates et al. 2012).

In the Pilbara, under an A2 (see Table 2.1 for definition) scenario, the annual average maximum daily temperature is projected to increase by 2.0–3.2°C by 2050 and 3.8–4.6°C by 2090. Annual average daily minimum temperatures will increase by 1.9–2.4°C and 4.1–4.6°C by 2050 and 2090 respectively (Bates et al. 2012).

2.4.2 Hot spells

Current trends

BoM defines hot spells as three or more consecutive days with daily maximum and minimum temperatures that are unusually high for that location (BoM viewed April 2016 www.bom.gov.au/australia/heatwave/about.shtml).

Steffen et al. (2014) defined hot spells as three or more days with temperatures over the 95th percentile for that location. Using this definition, they found the duration and frequency of hot spells generally increased across WA between 1950 and 2013, with the greatest increases in the Pilbara and interior. They also found the intensity decreased in the Kimberley and in coastal areas between Perth and Exmouth, and generally increased elsewhere.

Bates et al. (2012) defined hot spells as one or more days with temperatures over a threshold for that location. Thresholds for hot spells ranged from 40°C to 45°C in central and interior areas, to approximately 30°C in southern coastal areas; the threshold at Perth Airport was 37°C. Under this definition, hot spell intensity between 1958 and 2010 increased over most of WA, except in the far south-west, the north-west and southern Kimberley. The frequency increased over most of WA, except in the north-west and Kimberley, and the duration increased in the Pilbara and central areas and decreased in the Kimberley, west coast and southern areas.

In Perth between 1981 and 2011, the average number of heatwave days increased by three, the number of events increased by one, the length of the longest event increased by one day, the average heatwave intensity increased by 1.5°C and the first heatwave occurred three days earlier, compared to conditions between 1950 and 1980 (Steffen et al. 2014).

Future projections

Temperature extremes can be expected to increase in line with projected average temperatures (Steffen et al. 2014; Moise et al. 2015). The intensity of hot spells is projected to increase over most of WA; the frequency is projected to generally increase in the southern half of the state and the duration is projected to increase in northern coastal areas (Figure 2.10; Bates et al. 2012; Moise et al. 2015).

Perth could see the number of days with maxima over 35°C increase from 28 currently (1971–2000 average) to 36 in 2030 for RCP 4.5 and to 40 and 63 in 2090 for RCP 4.5 and RCP 8.5 respectively (Hope et al. 2015).

In Broome, the number of days with maxima over 35°C is projected to increase from 56 currently (1971–2000 average) to 87 in 2030 for RCP 4.5, and to 133 and 231 in 2090 for RCP 4.5 and RCP 8.5 respectively (Moise et al. 2015).

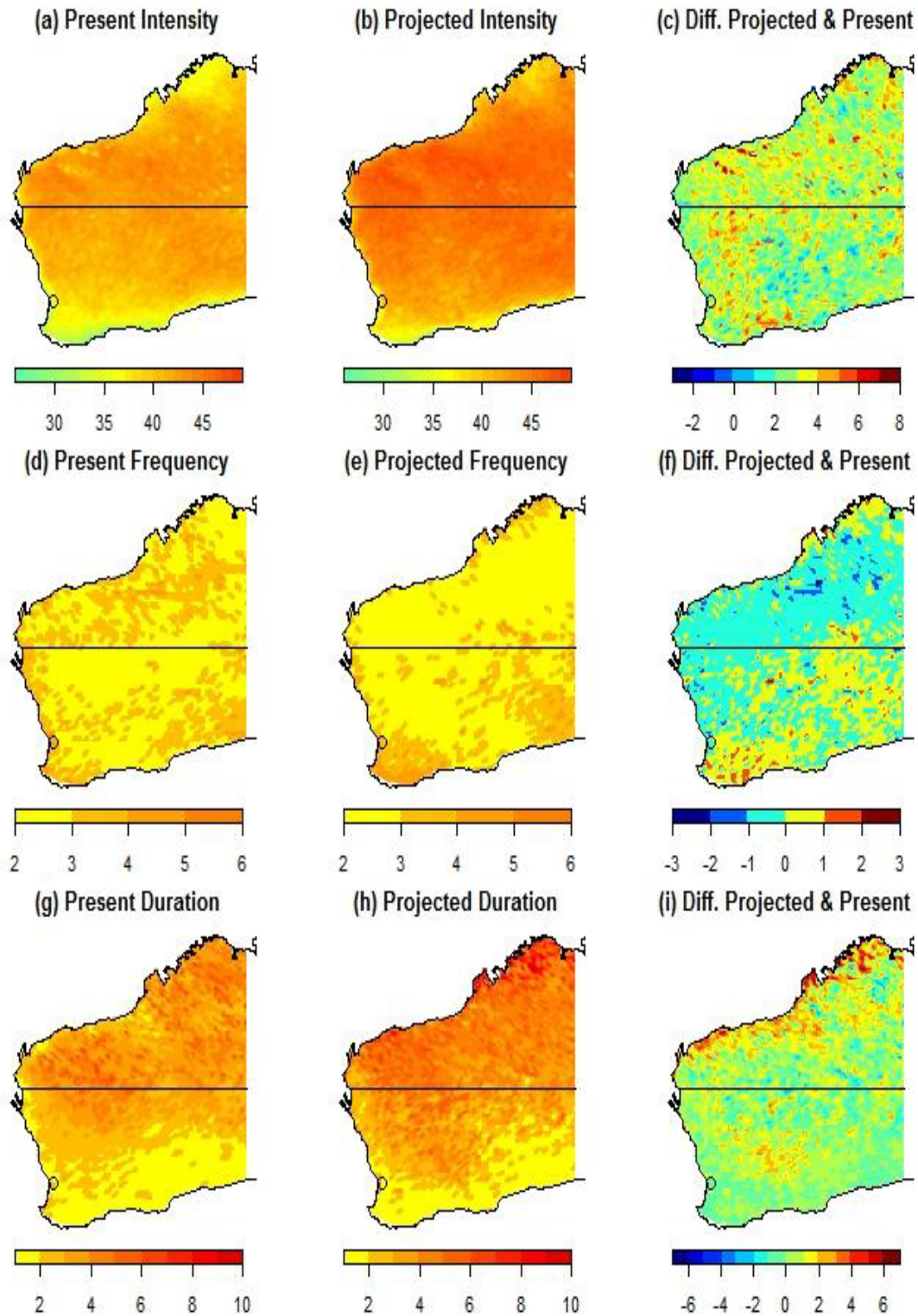


Figure 2.10 Hot spell characteristics: intensity (a) 1981–2010; (b) 2070–99 under a high-emission scenario (A2) and (c) their difference; frequency (d) 1981–2010; (e) 2070–99 and (f) their difference; duration (g) 1981–2010; (h) 2070–99 and (i) their difference. Intensity is expressed in °C, frequency is the number of events, and duration is expressed in days (Bates et al. 2012)

2.4.3 Frost

Current trends

Historically, the central and eastern parts of the wheatbelt have the greatest frost incidence and the northern and coastal areas have less risk (Figure 2.11). The frost window has increased in length by 2–4 weeks (Figure 2.12) and the start and end dates have shifted to later in the year (between September and November) in much of southern WA (Crimp et al. 2012). In contrast, the frost window declined by 2–5 weeks in southern coastal regions because of the mitigating effects of the maritime airflow. Much of southern WA showed an increase of up to six consecutive days with minimum temperatures at or below 2°C (Figure 2.13), with a 5–15% increase in the number of cold nights in the lowest 10th percentile of minimum temperatures for the period 1960–2010 (Crimp et al. 2012).

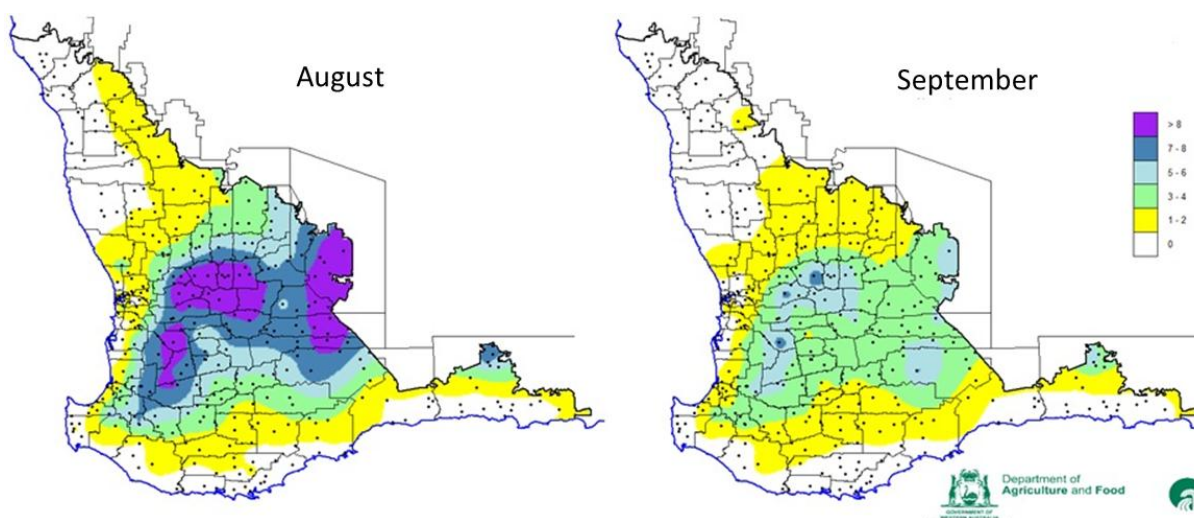


Figure 2.11 Average number of frost events (temperatures below 2°C) during August and September between 1975 and 2014 (DAFWA viewed March 2016 agric.wa.gov.au/agseasons/seasonal-climate-information)

Changes in frost occurrence have been particularly noticeable from the 1990s to the 2000s, which have been much drier. Increased frost risk has been attributed to stable, cloudless conditions associated with increased high pressure systems and changes in the position and intensity of the subtropical ridge (Crimp et al. 2012).

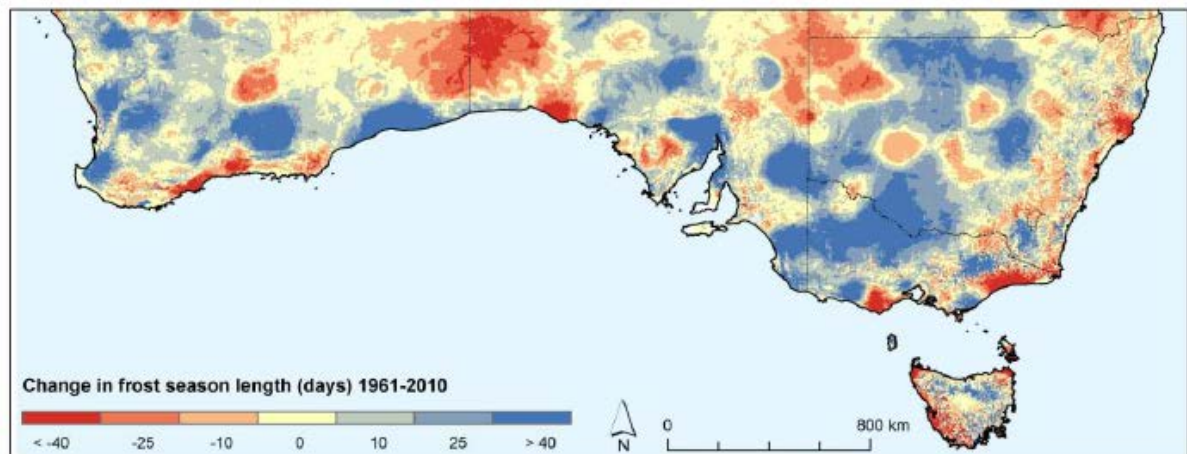


Figure 2.12 Trend in the frost season duration (average number of days per year) for the period August to November (1961–2010). Blue indicates areas with an increasing length of frost season and red indicates areas with a declining length (Crimp et al. 2012)

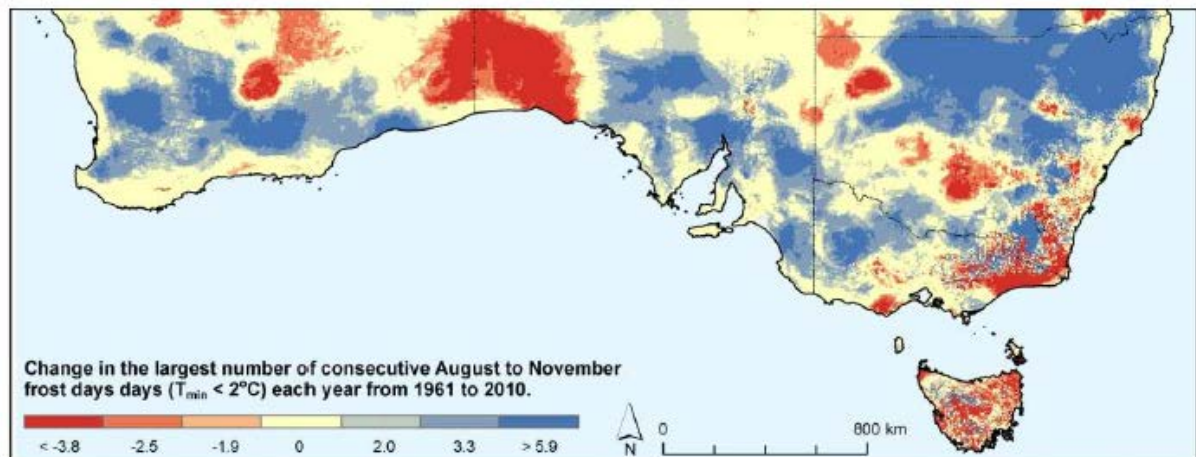


Figure 2.13 Trend in the number of consecutive frost events (temperatures below 2°C) for the period August to November (1961–2010). Blue indicates areas with an increasing number of consecutive frost events and red indicates areas with a declining number (Crimp et al. 2012)

Future projections

While climate models have difficulty reproducing the observed occurrence of frost, frost frequency is projected to decrease as temperatures increase (CSIRO & BoM 2007). For example, the incidence of frost in Perth is projected to decrease from the current average of 3.4 days per year to 2.1 days in 2030 and 0.9 days in 2090 under RCP 4.5 (Hope et al. 2015). It should be noted that minimum temperatures in winter and spring are likely to increase 10–15% more slowly than daily mean temperatures because of reduced cloud cover over southern Australia (CSIRO & BoM 2007).

2.4.4 Annual and seasonal rainfall

Current trends

Over the last 60 years, annual rainfall has increased over northern and interior WA and declined along the west coast, particularly the far south-west, where a decline of up 20% occurred (Figure 2.8; Bates et al. 2012). A recent study of tree growth in the Pilbara found that 5 of the 10 wettest years in the last 210 years occurred in the last two decades (O'Donnell et al. 2015). In contrast, declining rainfall in the wheatbelt has effectively resulted in a westward shift in rainfall zones by up to 100km in some areas, with relatively little change along the south coast (Figure 2.14). The decline in rainfall over the south-west is consistent with increasing greenhouse gas concentrations and cannot be explained solely by natural climate variability or changed land use such as land clearing (Bates et al. 2012).

Bates et al. (2012) linked increased rainfall in the Kimberley and the eastern Pilbara to an increase in the growth rate of the north-west cloud bands and an increase in the variability of the Madden-Julien Oscillation. Bates et al. (2012) suggested that particulate pollution from South-East Asia might be exerting a cooling effect on climate (Figure 2.2) and masking the effects of increasing greenhouse gas concentrations.

High sea surface temperatures off the north-west coast and increased summer rainfall in the Kimberley and Pilbara have coincided with major shifts in the large-scale atmospheric circulation of the southern hemisphere (Bates et al. 2012; Charles et al. 2013). These changes include a southward shift in the subtropical ridge and the southern hemisphere westerly jet stream (Cai et al. 2012; Abram et al. 2014; O'Donnell et al. 2015). In addition to increased annual rainfall, the seasonality — the difference between rainfall amount in the driest and wettest periods — has also increased in northern WA (Feng et al. 2013).

The decline in autumn and winter rainfall over the western Pilbara and south-west is attributed to the southward shift in the subtropical ridge and the southern hemisphere westerly jet stream (Bates et al. 2012; Cai et al. 2012; Charles et al. 2013; Abram et al. 2014). The associated strengthening of the southern hemisphere westerly jet stream and 17% reduction in the strength of the subtropical jet stream over Australia have reduced the likelihood of storm development over the south-west (Bates et al. 2012; Abram et al. 2014). A weaker subtropical jet stream leads to slower alternation of low and high pressure systems, and weaker surface low pressure systems and cold fronts. The stronger southern hemisphere westerly jet stream is associated with low pressure anomalies over Antarctica and high pressure anomalies over the mid-latitudes. Consequent rainfall reductions are associated with the persistence of high pressure systems over the region, so while intense rainfall events still occur they are interspersed by longer dry periods.

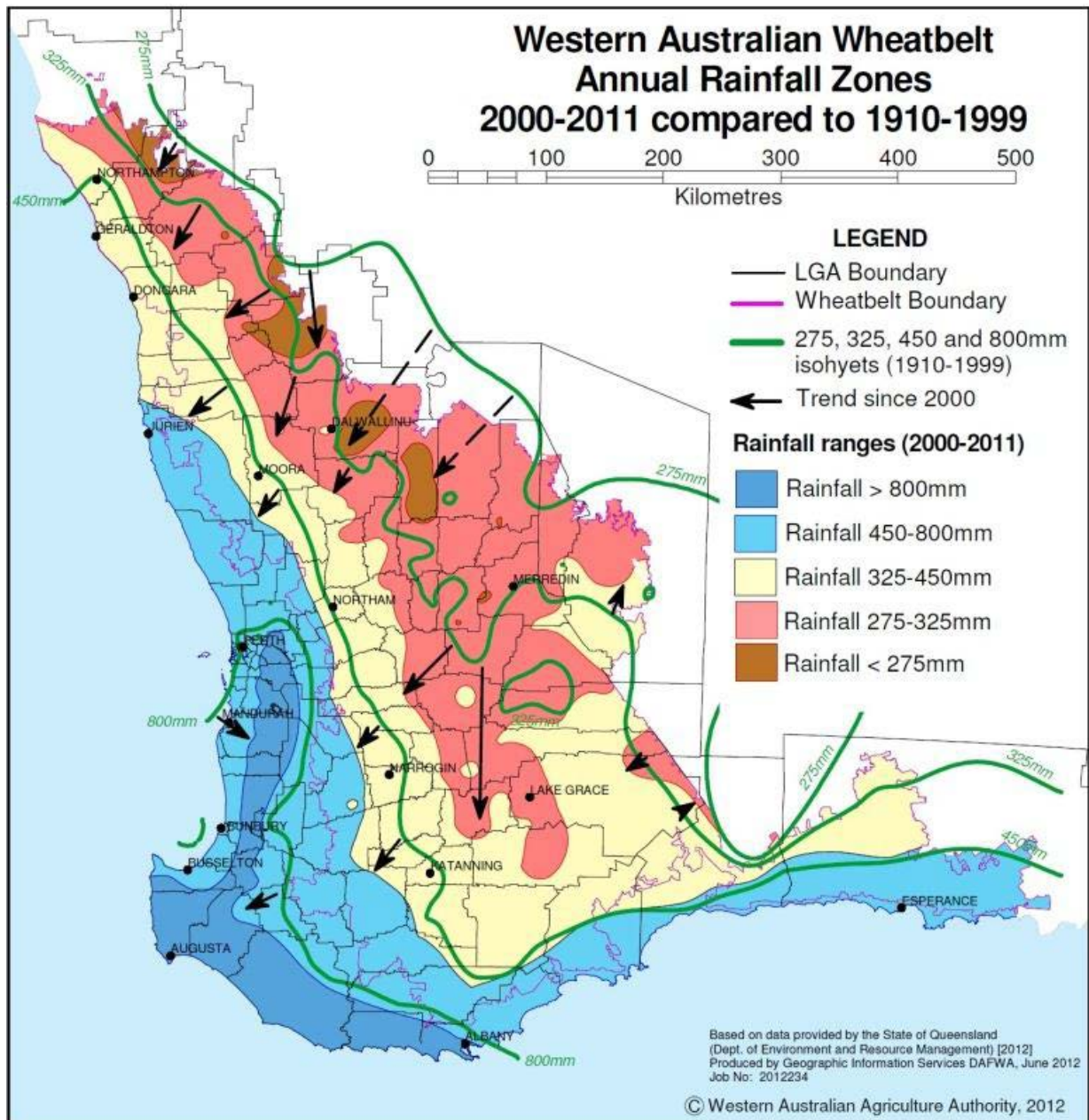


Figure 2.14 Average annual rainfall for the south-west of WA from 1910–99, compared to 2000–11 (Guthrie et al. 2015)

Future projections

Climate models indicate that the drying trend in the south-west will continue as greenhouse gas concentrations increase (Figure 2.15). The projected future changes differ a little from the observed changes in recent years. There may be an increase in the occurrence of synoptic systems bringing rainfall to the wheatbelt and south coast, but the projected drop in the number of deep low pressure systems means much less rainfall for the western coastal regions and far south-west. The overall increase in average pressure will likely drive a further shift to a more settled weather regime, with more highs persisting for longer (Bates et al. 2012).

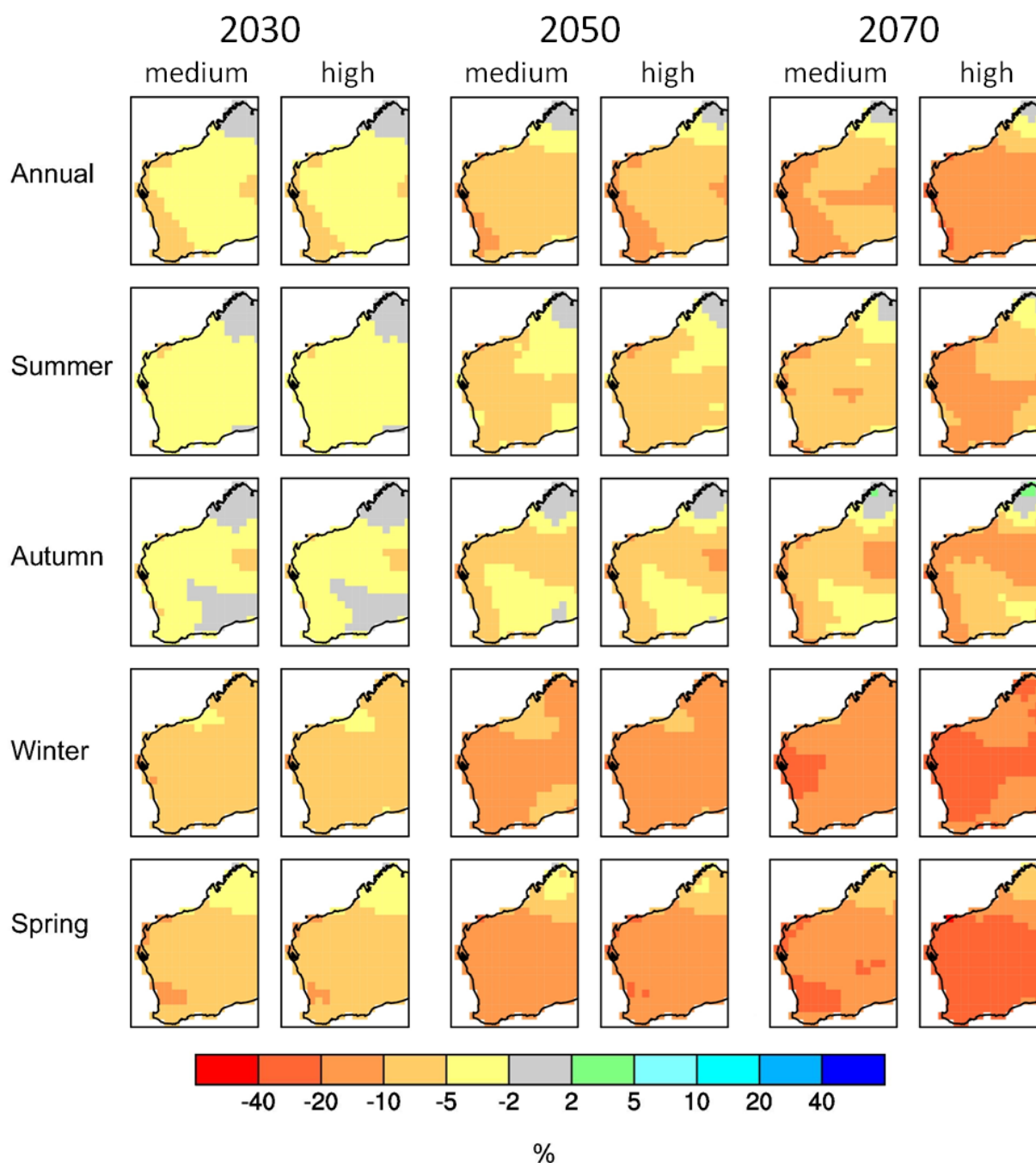


Figure 2.15 Average projections from five global climate models for annual and seasonal total rainfall change for 2030–70. Projections are relative to the period 1980–99. Emission scenarios are from the IPCC's *Special Report on Emission Scenarios*, where medium is the A1B scenario and high is the A1F1 scenario (see Table 2.1 for definition of scenarios; BoM, viewed July 2013 — link no longer active)

There is high confidence (Appendix A) that annual, winter and spring rainfall will decline in the south-west. The average of rainfall projections for the south-west with an intermediate-emission scenario (RCP 4.5) is for a 6% reduction in annual rainfall by 2030 and a 12% reduction by 2090 (range 1–15% reduction) compared to average conditions between 1986 and 2005 (Appendix B; Hope et al. 2015). For a high-emission scenario (RCP 8.5), reductions are 5% by 2030 and 18% by 2090

(range 5–35% reduction) (Hope et al. 2015). Rainfall declines are greatest during winter and spring, at 29% and 36%, respectively, by 2090 for RCP 8.5 (Hope et al. 2015).

Changes in projected rainfall for the Monsoonal North are small compared to the current natural variability and there is generally *low confidence* in projected rainfall changes. While the median projection is for rainfall to decline by 8–18% in the comparatively dry winter and spring months, unchanged or slightly increased rainfall during summer means that projected annual rainfall changes are less than or equal to 1% for RCP 4.5 and RCP 8.5 scenarios in 2090, compared to average conditions between 1986 and 2005 (Moise et al. 2015).

Recent modelling for the Pilbara using 18 CMIP5 global climate models found little change in annual rainfall for the RCP 4.5 scenario and median rainfall reductions of 1.5% by 2030 and 2% by 2050 for the RCP 8.5 scenario (Charles et al. 2013). Rainfall is projected to decrease in western areas of the Pilbara and increase in eastern areas (Charles et al. 2013).

2.4.5 Rainfall intensity

Despite declining annual rainfall across much of the state, there is medium to high confidence that the intensity of heavy rainfall events will increase but there is low confidence in projections of the magnitude of that change (Figure 2.16b; Hope et al. 2015; Moise et al. 2015). CMIP5 projections are for the average maximum one day rainfall in 2090 to increase by about 6% in the south-west and 9% in the Monsoonal North for RCP 4.5, and 15% and 20%, respectively, for RCP 8.5, compared to average conditions from 1986 to 2005 (Hope et al. 2015; Moise et al. 2015).

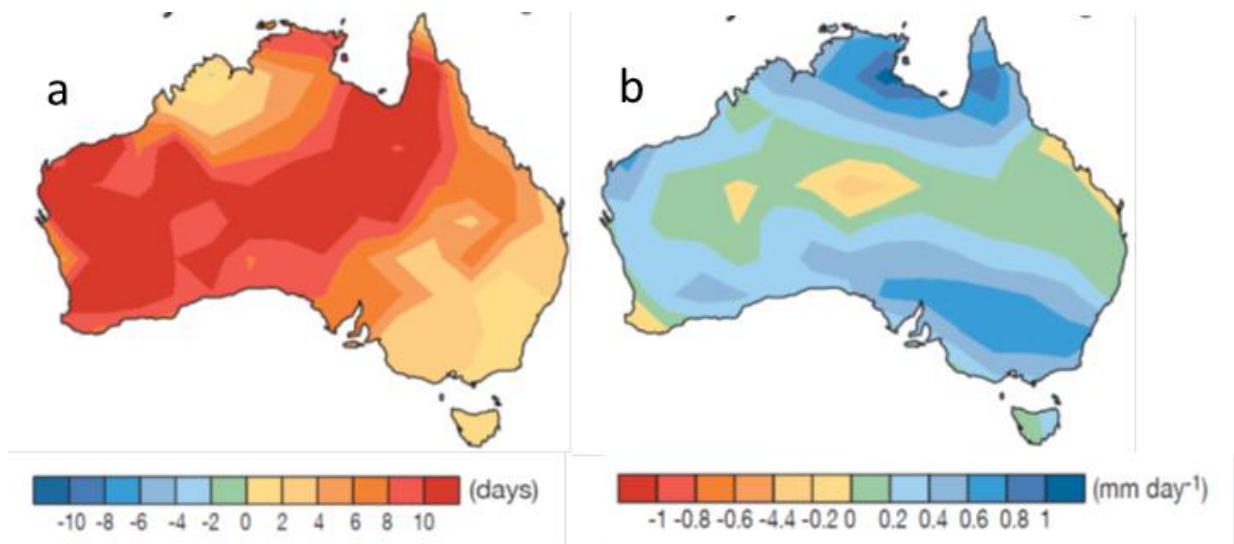


Figure 2.16 (a) Change in the number of dry days; and (b) rainfall intensity over Australia in 2080–99, compared to 1980–99 for the A1B (see Table 2.1 for scenario definition; CSIRO & BoM 2007)

2.4.6 Drought

The number of dry days is likely to increase over all of WA (Figure 2.16a). CSIRO and BoM (2007) define agricultural drought as a period of extremely low soil moisture and found that there were likely to be up to 20% more drought months over most of Australia by 2030 and up to 80% more in the south-west by 2070. Kirono et al. (2011) suggested there is more than 66% probability) that drought will affect twice as much of southern WA and/or twice as often by 2030.

Hope et al. (2015) found that the projected duration and frequency of droughts in the south-west increased for all emission scenarios with these increases becoming large by 2090 (for RCP 8.5). There is high confidence in these projections (Figure 2.17).

Drought can be expected to continue to be an occasional feature of the Kimberley climate, but there is low confidence in projections of how the frequency or duration may change.

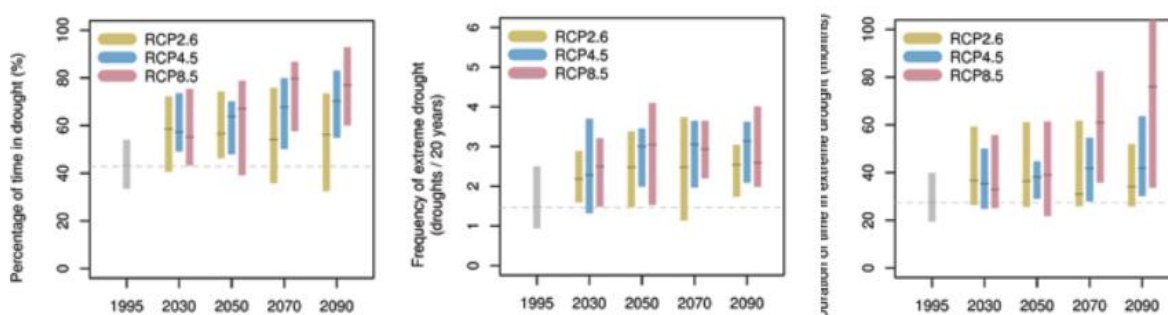


Figure 2.17 Projected changes in drought in the south-west based on the Standardised Precipitation Index for various emission scenarios and time periods; grey bar represents current conditions (Hope et al. 2015)

2.4.7 Agricultural water supplies

In 2011–12, 337 giganlitres (GL) of water was used on farms; this amount was 24% of the total 1420GL of water used in WA (ABS 2013b, 2013c). Groundwater, large dams and on-farm dams or tanks were the primary sources of water used on farms (Table 2.3). Irrigation was the largest component of total agricultural water use at 73%, with pasture and fodder production being the largest users of irrigation water (Table 2.4). Compared to the rest of Australia, WA uses the most irrigation water on a per hectare basis at 4.9ML/ha (ABS 2013b).

Figure 2.18 shows the size and location of surface water resources in WA. The largest available source is the Ord River Dam, with smaller resources available in the far south-west. The largest groundwater resources are along the Swan Coastal Plain (Figure 2.19). Most of these resources have more than 70% of the allocation committed. The largest available groundwater resources are in the Northern Agricultural, Mid West and Gascoyne regions.

Table 2.3 Sources of water used on WA farms in 2011–12 (ABS 2013b)

Water source	Amount of water used (GL)
Groundwater	127.9
Water taken from irrigation channels	100.3
Water taken from on-farm dams or tanks	80.0
Town or country reticulated mains supply	14.8
Water taken from rivers, creeks, lakes	12.2
Other sources	0.8
Recycled/re-used water from off-farm sources	0.7

Table 2.4 Irrigation enterprises and the amount of irrigation water used in WA in 2011–12 (ABS 2013b)

Agricultural activity	Number of businesses	Area irrigated (ha)	Water applied (GL)
Pastures and cereal crops for livestock feed	674	11 545	61.8
Vegetables for human consumption	522	9 513	57.7
Fruit trees, nut trees, plantation or berry fruits	731	7 840	39.3
Other cereals for grain or seed	57	4 222	17.0
Other broadacre crops	16	1 294	12.0
Grapevines	584	9 911	10.8
Nurseries, cut flowers and cultivated turf	236	1 243	9.9
Cotton	11	820	8.1
Pastures and cereal crops cut for hay	53	894	5.2
Rice	2	84	1.0
Pastures and cereal crops cut for silage	21	117	0.9
Sugar cane	1	6	0.1
Total	2676	50 058	246

Climate change is contributing to reduced rainfall, declining inflows to public water supply dams and declining recharge to groundwater sources in the south-west. Reduced rainfall and run-off is concerning to producers and combined with an estimated 40% increase in the state's population by 2030, there will be an increase in competition for scarce water resources from urban and industrial users (Petroni et al. 2010).

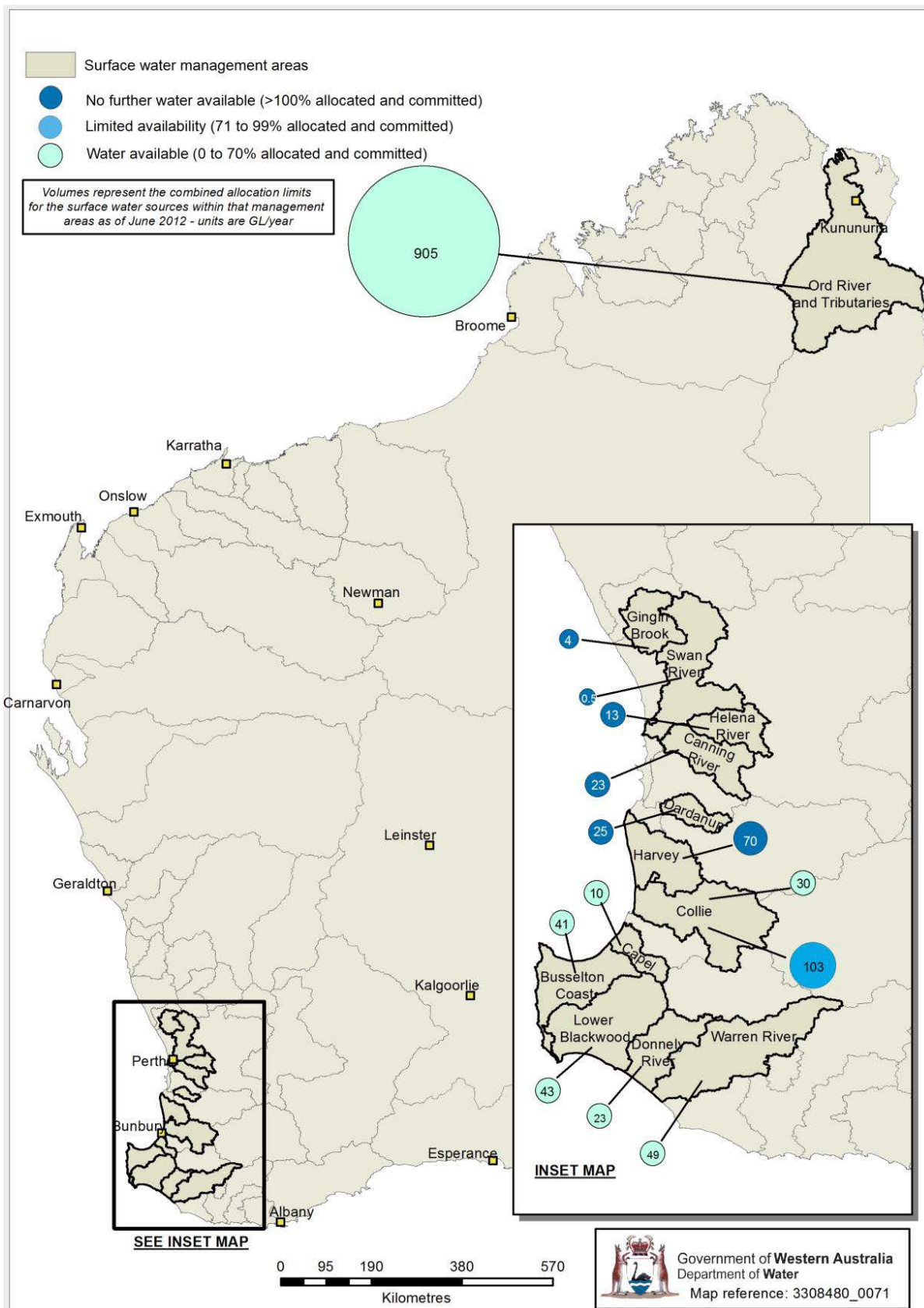


Figure 2.18 Surface water resources available for allocation (GL/y displayed in circles) and percentage of resource that is allocated (colour of circle) in WA (Department of Water 2014a)

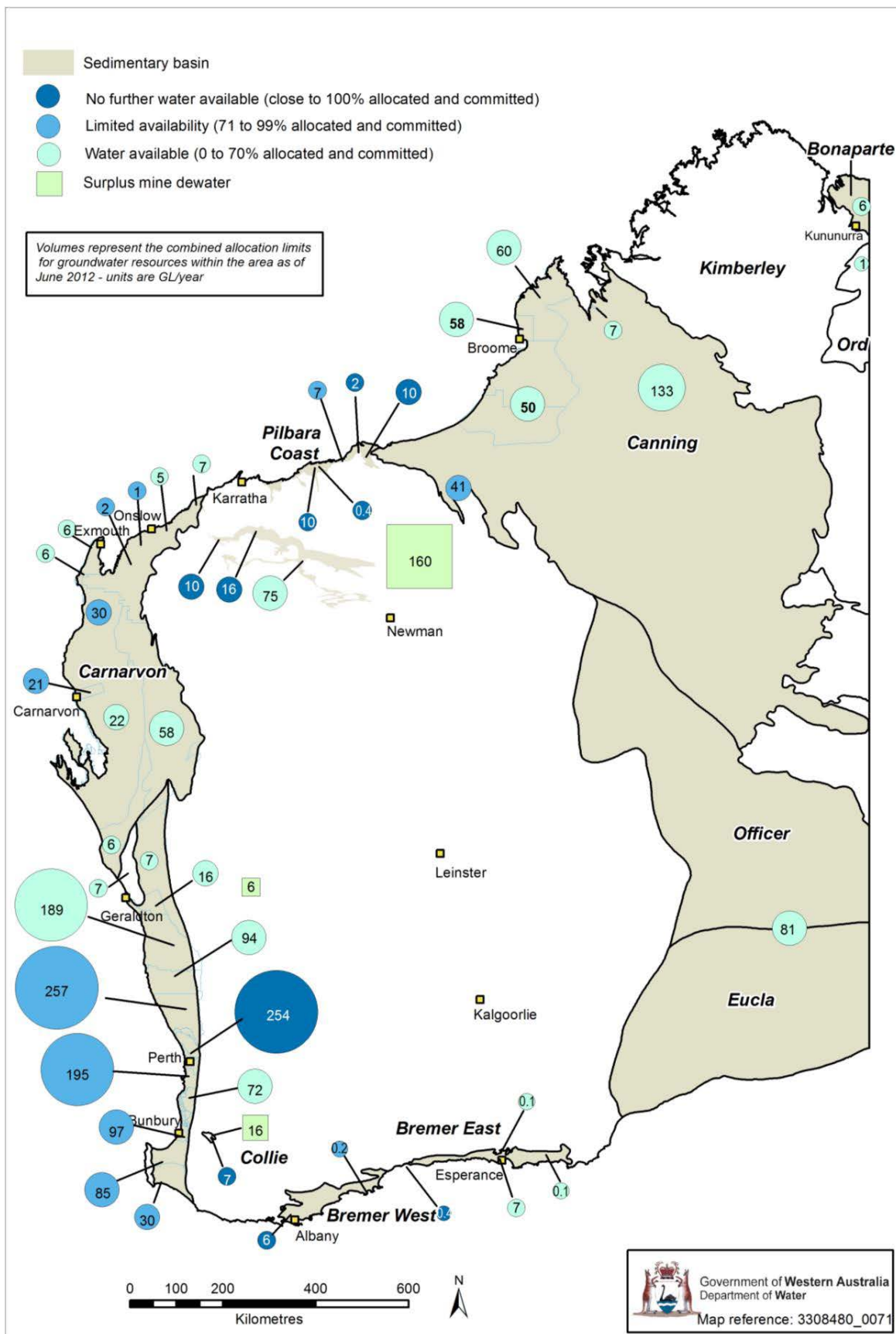


Figure 2.19 Groundwater resources available for allocation (GL/y displayed in circles and squares) and percentage of resource that is allocated (colour of circles and squares) in WA (Department of Water 2014a)

Warmer, drier conditions forecast for much of WA mean that broadacre agriculture will need to adapt to lower annual rainfall and perhaps changed seasonality. Irrigated agriculture will need to deal with reduced water entitlements and perhaps less reliability of annual allocations (Meyer & Tyerman 2011).

Current trends

The Department of Water monitors surface water and groundwater resources across WA. Water level trends are an indicator of how the resources are responding to current climate and abstraction (Department of Water 2014a). Where surface water has been monitored, there has been a trend over the last 10 years for streamflow to increase in the Kimberley and decrease in the south-west (Table 2.5).

Table 2.5 Average annual streamflow trend (2002–12), expressed as the number of surface water management areas in each category for each region (Department of Water 2014a, 2014b)

Region	Water quality	Streamflow trend
Kimberley	Fresh	15 increasing, 1 not assessed
Pilbara	No data	3 not assessed
Gascoyne	Fresh	5 not assessed
Mid West	No data	10 not assessed
Wheatbelt	No data	1 decreasing, 7 not assessed
Perth	Mostly fresh	6 decreasing, 1 not assessed
Perth South	Mostly fresh	8 decreasing, 1 not assessed
Peel	Fresh to saline	1 seasonal, 9 decreasing, 1 not assessed
South-West	Fresh to brackish	17 decreasing, 2 not assessed
Great Southern	No data	4 decreasing
Goldfields Esperance	No data	4 not assessed

Changes in groundwater recharge and groundwater level have not been consistent spatially or consistently downward (Dawes et al. 2012). In addition to rainfall, recharge and storage also depend on land cover, soil type and watertable depth (Ali et al. 2012; Dawes et al. 2012). Where aquifers have been measured, levels are generally stable or seasonal in the Kimberley, Pilbara and Gascoyne regions; increasing, stable or seasonal in the Mid West; and stable or decreasing in the rest of the state (Table 2.6)

Table 2.6 Groundwater quality (F = fresh, M = marginal, B = brackish, S = saline) and groundwater level trend (2001–12), expressed as the number of aquifers in each category for each region (n/a = not assessed; Department of Water 2014a, 2014b)

Region	Aquifer depth	Water quality	Aquifer level trend
Kimberley	Shallow	Mostly F	1 increasing, 14 stable, 9 n/a
	Medium	F–B	11 stable, 5 n/a
	Deep	No data	2 n/a
Pilbara	Shallow	F–B	18 seasonal
	Medium	Mostly S	2 seasonal
Gascoyne	Shallow	F–S	3 stable, 11 seasonal, 1 n/a
	Medium	S	7 stable, 1 n/a
	Deep	B–S	2 stable
Mid West	Shallow	M–S	1 increasing, 3 stable, 11 seasonal, 4 n/a
	Medium	F–S	1 increasing, 1 stable, 2 seasonal, 2 n/a
	Deep	F–S	3 increasing, 5 stable, 2 decreasing
Wheatbelt	Shallow	F–S	7 stable, 9 decreasing
	Medium	F–B	1 increasing, 4 decreasing
	Deep	F–S	1 increasing, 6 decreasing
Perth	Shallow	F–B	2 stable, 38 decreasing
	Medium	F–B	15 decreasing
	Deep	F–S	7 decreasing
Perth South	Shallow	F–B	12 stable, 32 decreasing, 4 n/a
	Medium	F–B	16 decreasing
	Deep	F–S	22 decreasing
Peel	Shallow	F–B	1 stable, 7 decreasing, 3 n/a
	Medium	M–B	6 decreasing, 8 n/a
	Deep	F–S	3 decreasing, 3 not assessed
South-West	Shallow	F–S	2 increasing, 12 stable, 5 decreasing, 23 n/a
	Medium	Mostly F	4 stable, 11 decreasing, 4 n/a
	Deep	Mostly F	1 stable, 9 decreasing, 5 n/a
Great Southern	Shallow	Mostly F	1 stable, 5 n/a
	Medium	Mostly F	5 stable 2 n/a
Goldfields Esperance	Shallow	F–S	14 stable, 3 decreasing, 4 n/a
	Medium	M	8 stable, 5 n/a
	Deep	No data	3 stable

Declining rainfall over the past 30 years, coupled with increasing water demand from a growing population, has resulted in declining water storages in dams and aquifers in the south-west (Petroni et al. 2010). Historically, around 10% of rainfall would run-off into Perth's water supply catchments but run-off has declined by nearly two-thirds (Silberstein et al. 2012). Falling soil moisture and groundwater levels, and the decoupling of groundwater and surface water connectivity may drive this decline, so baseflow in streams now stops during summer (Petroni et al. 2010). Consequently, the contribution of surface water catchments to Perth's drinking water supply has fallen from 80% in the 1970s to less than 40% now, with the rest coming from groundwater and desalinated seawater (Petroni et al. 2010).

Some groundwater systems in the south-west are also suffering over-allocation problems and likely over-use problems. Bennett and Gardner (2014) list seven groundwater management areas in the south-west that are over-allocated. As an example of how the drying climate is a factor, they cite the 2009 reduction in allocation limits (but not licensed entitlements) for some management units in the Gngangara system to reflect reductions in groundwater recharge.

Besides the impact of reduced rainfall on major groundwater and surface water resources, it could be expected that reduced run-off will similarly affect on-farm water catchments and inflows to farm dams. Most broadacre farms in the south-west are supplied with water from on-farm dams with a variety of rainwater harvesting catchments. Current design standards for farm dam catchments are based on run-off occurring when total daily rainfall exceeds 10mm. However, the number of daily rainfall events above this threshold is declining in the south-west. Consequently, the number of water supply failures or water shortages has increased in recent years (Baek & Coles 2013).

Future projections

Projected climate change is expected to further reduce streamflow (run-off; Figure 2.20) into dams and groundwater recharge in western and south-western areas of the state. The resulting impact on surface water and groundwater resources is likely to be profound (Barron et al. 2011; Silberstein et al. 2012). The relationship between rainfall and water yield is nonlinear so an 11% decline in rainfall (by 2050 under an SRES A2 emission scenario) would result in a 31% decline in water yield for catchments along the Darling Scarp (Berti et al. 2004).

Hope et al. (2015) project that run-off in the south-west will decline by about 45% for RCP 4.5 and 64% for RCP 8.5 by 2090 (median values). The median forecast for an 8% decline in rainfall across the south-west by 2030 (Figure 2.15) is projected to reduce streamflow by 24% (Silberstein et al. 2012). The 10th and 90th percentiles of rainfall reduction are 2% and 14%, resulting in 2% and 42% reductions in streamflow, respectively, across the region. These reductions will be in addition to the more than 50% reduction in streamflow that occurred between 1975 and 2012 (Silberstein et al. 2012).

The northern part of the south-west is projected to experience a 53% decline in run-off. Because this area has most of Perth's major drinking water supply reservoirs, a

decline of this magnitude would have a significant effect on reservoir inflows, water resources planning and the value of the dams themselves (Silberstein et al. 2012).

Given the uncertainties about projected changes in rainfall seasonality and intensity in the Monsoonal North, there is low confidence (Appendix A) in projections of run-off (Moise et al. 2015).

Surface water and aquifers in the Perth Basin and aquifers in the Murchison and Gascoyne regions are considered likely to be highly affected by changes to recharge that are driven by climate change (Figure 2.21; Barron et al. 2011). Reduced recharge and run-off is likely to adversely affect irrigated agriculture in those areas. Aquifers in the Pilbara are considered to be sensitive to climate change while the aquifer underlying the developing irrigation area south-east of Broome is considered to have low sensitivity to climate change (Barron et al. 2011).

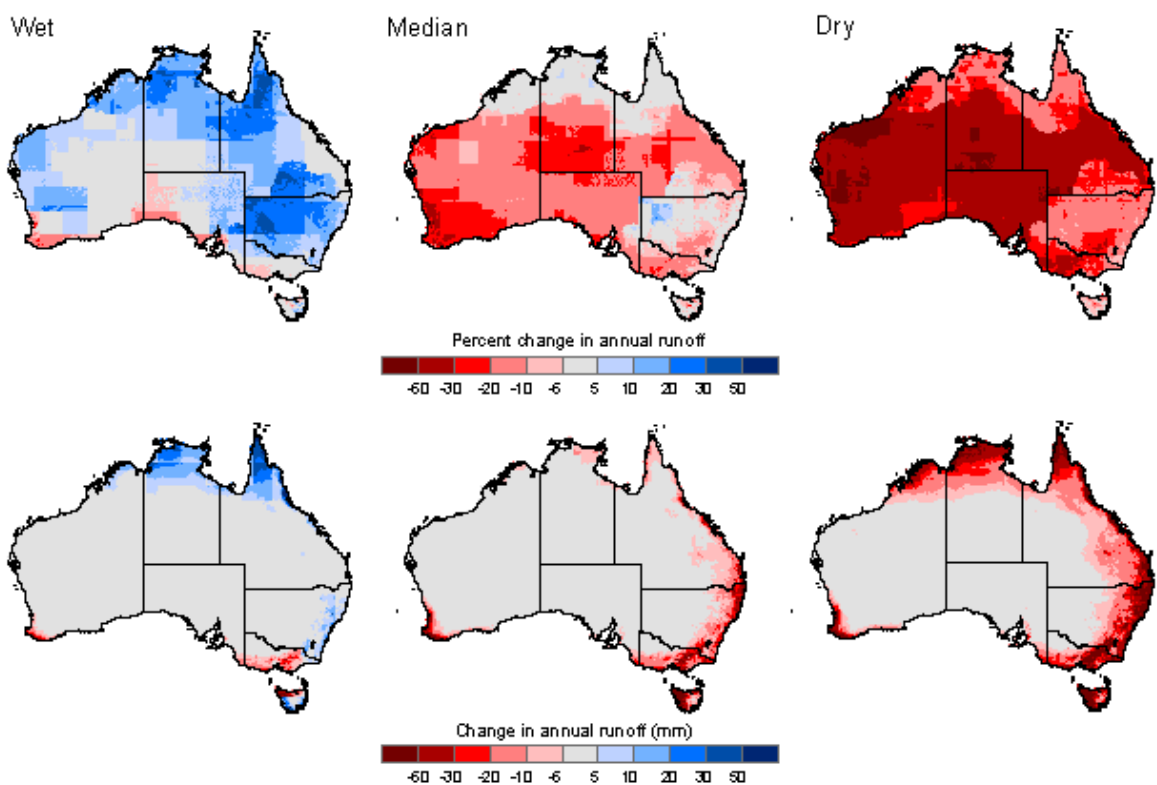


Figure 2.20 Projected changes in annual run-off for wet (2% reduction in rainfall in south-west WA), median and dry (14% reduction in rainfall in south-west WA) climates in 2030 with 1°C temperature increase relative to 1990 (Chiew 2010 cited in Barron et al. 2011, p. 59)

While the impacts of climate change on coastal groundwater resources are not well understood, increasing demand for fresh water in coastal areas, rising sea level and variations in rainfall recharge may result in increases in the incidence and severity of seawater intrusion, which can significantly degrade water quality and reduce freshwater availability (Ivkovic et al. 2012). A vulnerability factor analysis based on groundwater levels, rainfall, groundwater salinity and groundwater extraction showed aquifers at Derby, Esperance, Exmouth and Perth (Whitfords and Cottesloe) were highly vulnerable to saltwater intrusion in the future (Ivkovic et al. 2012). Aquifers at

Broome and Carnarvon were moderately vulnerable to saltwater intrusion, aquifers at Bunbury had low and high vulnerability and aquifers at Albany had low and moderate vulnerability (Ivkovic et al. 2012). The Peel–Harvey area is topographically flat, with low hydraulic gradients towards the ocean. A small decline in watertables is projected to change groundwater flow direction and increase the risk of seawater intrusion under a future dry climate (Ali et al. 2012).

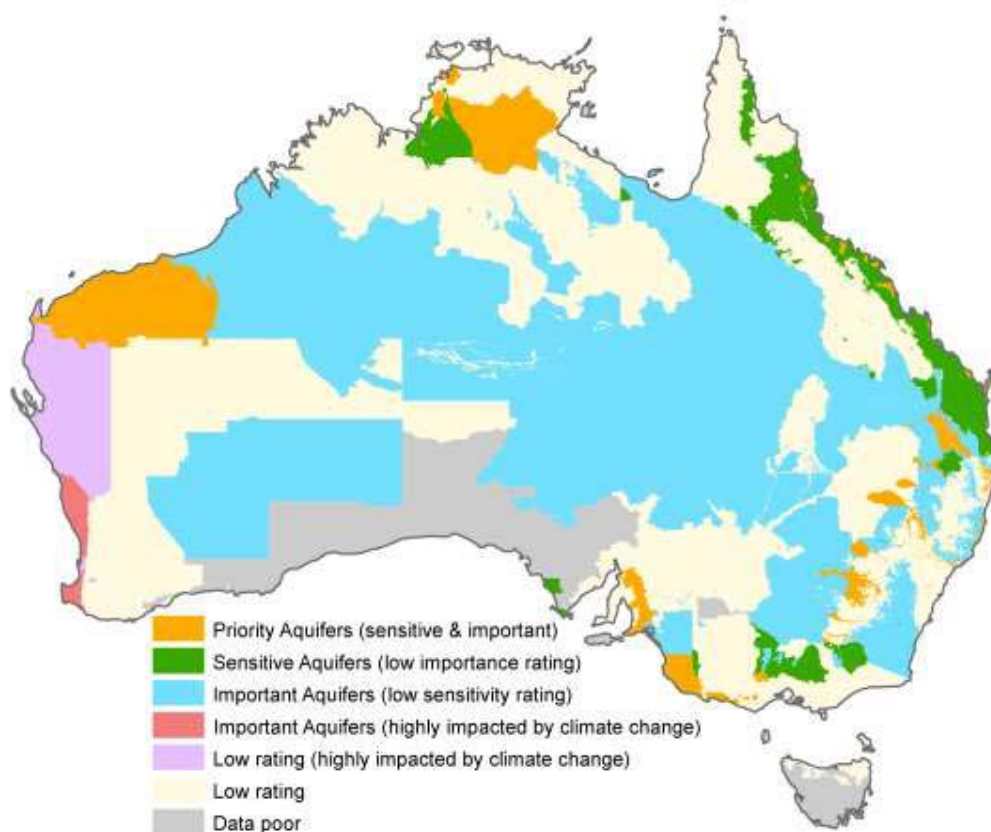


Figure 2.21 Location of priority, sensitive and important aquifers (Barron et al. 2011)

2.4.8 Tropical cyclones

Current trends

Tropical cyclones are responsible for most of the extreme rainfall events across north-west WA and generate up to 30% of the total annual rainfall near the Pilbara coast. While tropical cyclones make a valuable contribution to rainfall in the north-west, interannual and spatial variability strongly affects the reliability of this rainfall as a source for water supplies (Bates et al. 2012; Charles et al. 2013).

As well as providing valuable rainfall, tropical cyclones produce extreme wind, rainfall and storm surges that threaten life, property and the environment. The area between Broome and Exmouth has the highest frequency of tropical cyclones crossing the coast of the entire Australian coastline. Over the last 40 years, the frequency of tropical cyclones has not changed significantly across the north-west; however, there is some evidence that the frequency of the most intense tropical cyclones has increased (O'Donnell et al. 2015). An examination of stalagmites in WA suggests that a repeated centennial cycle of tropical cyclone activity has occurred, with a sharp

decrease in activity after 1960, so that tropical cyclone activity is now at its lowest level for the last 1500 years (Haig et al. 2014).

Over the last 30 years, the latitude at which tropical cyclones reach their maximum intensity has increased at a rate of about one degree per decade (63km/decade) in the southern hemisphere (Kossin et al. 2014).

Future projections

Tropical cyclone frequency is projected to decline and intensity is expected to increase throughout the century (Moise et al. 2015; Watterson et al. 2015). Modelling by Bates et al. (2012) suggests that the frequency of tropical cyclones may decrease by as much as 50% by the end of the century, with rainfall intensity increasing by 23% within 200km of the storm centre and 33% within 300km of the storm centre.

Haig et al. (2014) suggest that planning for tropical cyclone risk should be undertaken on the basis that WA is currently at the minimum of a centennial cycle of tropical cyclone frequency and that tropical cyclone frequency may increase in the future despite climate models projecting a decline in frequency. They warn that this natural increase in frequency could be combined with an increase in intensity caused by climate change.

2.4.9 Evaporative demand

Future projections

Figure 2.22 shows projected evaporative demand initially decreasing in southern and central parts of WA, then generally increasing after 2030, with the greatest changes occurring in the far north and south.

In the south-west, CMIP5 projections provide high confidence that potential evaporation will increase in 2030 and increase substantially in 2090. However, there is only medium confidence (Appendix A) in the projected magnitude of the changes (Appendix B4, Hope et al. 2015). Relative changes will be greatest in winter and autumn, but absolute changes will be greatest in summer. Median projections are for annual potential evaporation to increase in 2030 by 2.5% under RCP 4.5 and 2.8% for RCP 8.5; and to increase in 2090 by 5.4% under RCP 4.5 and 10.3% under RCP 8.5 (Appendix B4).

In the Monsoonal North and Rangelands regions, there is high confidence that evaporative demand will increase but only medium confidence in the magnitude of projections (Moise et al. 2015; Watterson et al. 2015).

In the Monsoonal North, increases are projected to be greatest during autumn and winter (when rainfall is projected to decline) and least in spring and summer (Appendix B1; Moise et al. 2015). Projected median change in annual evaporation in 2030 is 3.9% under RCP 4.5 and 3.1% under RCP 8.5; and in 2090, it is 6.5% under RCP 4.5 and 12.4% under RCP 8.5 (Appendix B1).

In the rangelands regions, increases are projected to be similar throughout the year, relative to current conditions, but greatest during summer in absolute terms (Appendices B2 and B3; Watterson et al. 2015). Projected median changes in annual

evaporation are between 2.5% (RCP 4.5) and 3.0% (RCP 8.5) in 2030 and between 4.7% (RCP 4.5) and 5.1% (RCP 8.5) in 2090 (Appendices B2 and B3).

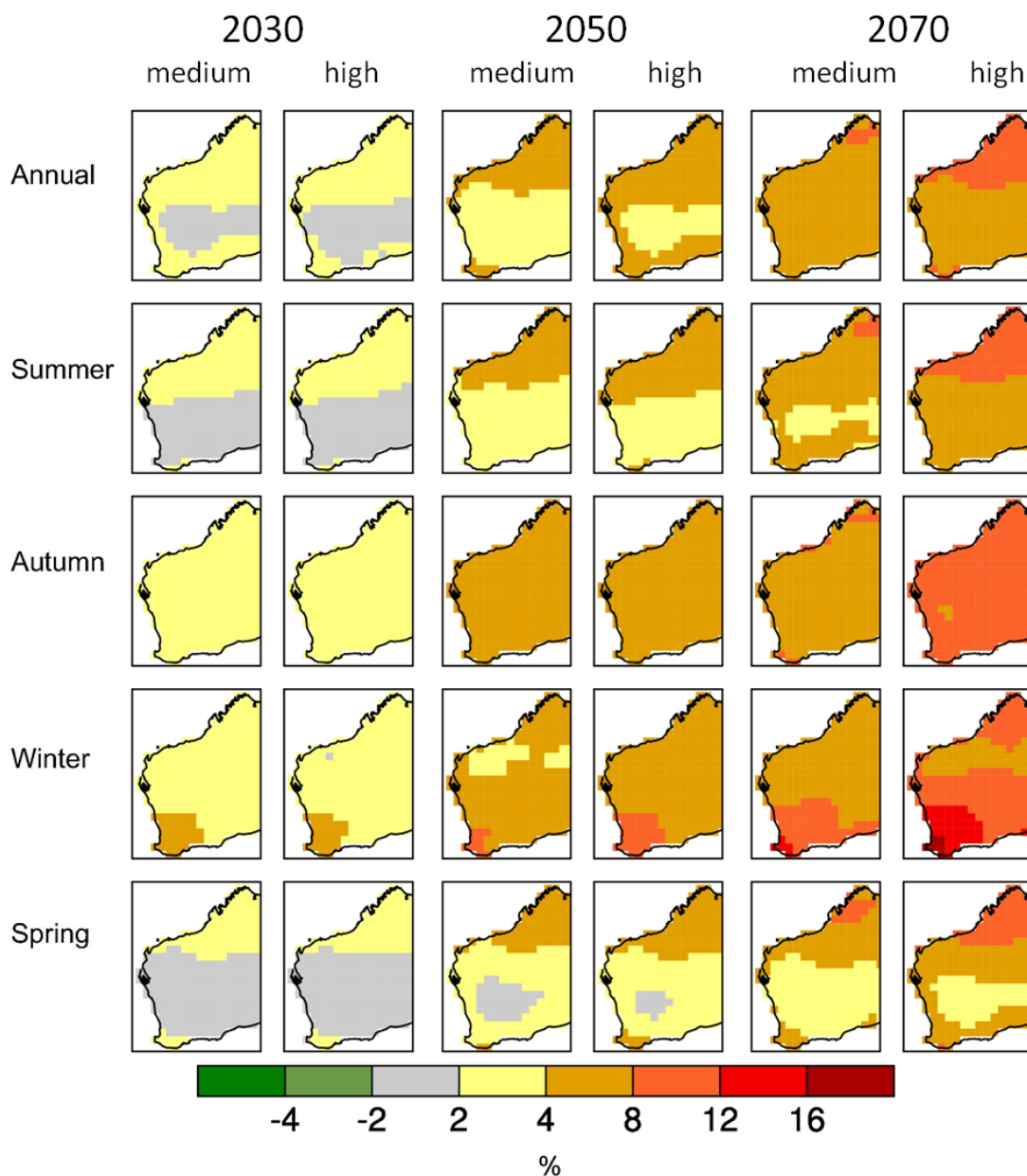


Figure 2.22 Annual and seasonal total pan evaporation change for 2030–70. Projections are relative to the period 1980–99. Emission scenarios are from the IPCC’s *Special Report on Emission Scenarios*. Medium is the A1B scenario and high is the A1F1 scenario (see Table 2.1 for definitions of scenarios; BoM, viewed July 2013 — link no longer active)

Modelling for the Pilbara using CMIP5 global climate models showed median potential evaporation increases of 3.0% and 4.6% by 2030 and 2050, respectively, for RCP 4.5, and increases of 3.4% and 6.5%, respectively, for RCP 8.5 (Charles et al. 2013). It should be noted that a 3–4.6% change in evaporative demand in the high evaporative demand Pilbara environment (Figure 2.8) is greater in absolute terms than a 10.3% increase in the lower evaporative demand environment of the south-west.

2.4.10 Wind speed

Future projections

While there is high variability in wind speed projections between global climate models, the CMIP3 and CMIP5 modelling show relatively small changes in average annual wind speed (Figure 2.23; CSIRO & BoM 2007; Hope et al. 2015; Moise et al. 2015; Watterson et al. 2015).

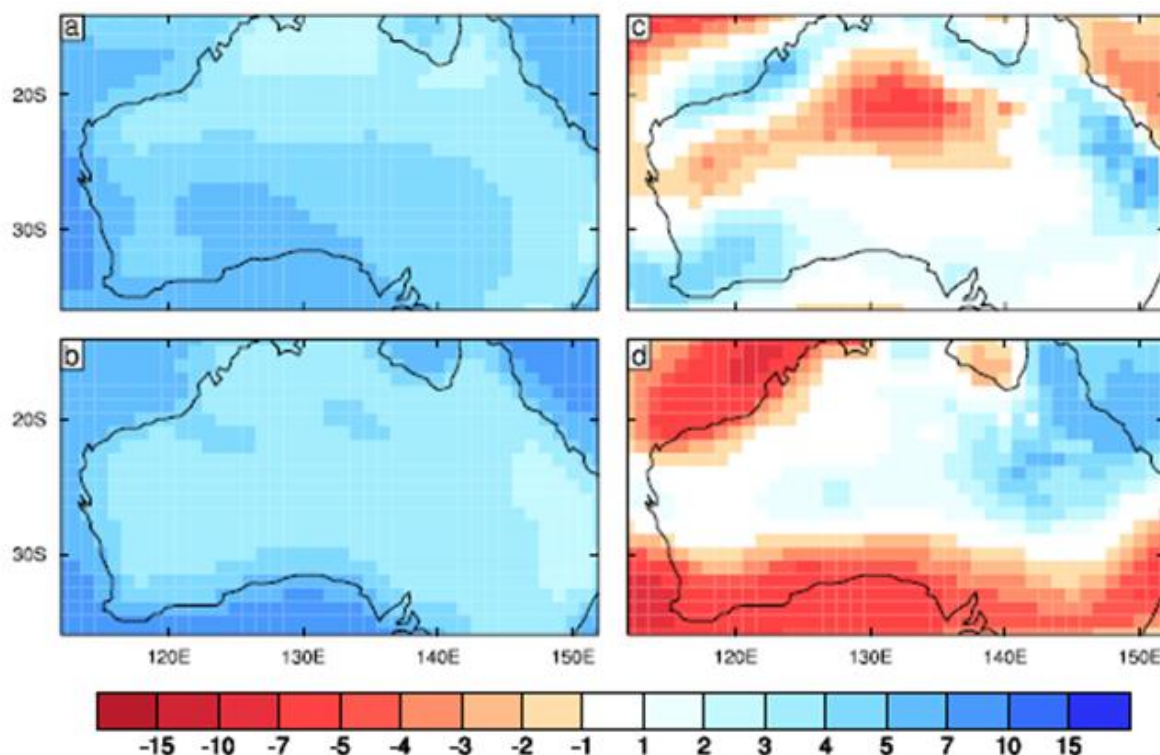


Figure 2.23 Average wind speed (metres per second (m/s)) for 1986–2005 during (a) summer and (b) winter; and percentage change in median projected wind speed during (c) summer and (d) winter in 2090 for RCP 8.5 (Watterson et al. 2015)

In the south-west in 2090 under RCP 8.5, there is high confidence that projected wind speed will decrease in winter (median -4.2%) and low confidence of an increase in summer (median 2.3%), with an annual change of less than 1% (Appendix B4; Hope et al. 2015). Projected wind speed changes in 2030 are $\pm 2\%$ for all RCPs (Hope et al. 2015).

In the Monsoonal North and Rangelands regions, there is medium to high confidence that there will be little change in wind speed in 2030 or 2090 under any emission trajectory (Appendix B; Moise et al. 2015; Watterson et al. 2015).

2.4.11 Fire risk

Fire is a natural part of Australia's ecosystems, with distinct regional variations in seasonality and frequency (Figure 2.24). In the north, fire danger is greatest during the dry winter and spring, with some tropical savanna woodlands and grasslands burning every year. In the south, fire danger is greatest during the dry summer and autumn period, with temperate heathlands and dry sclerophyll forests burning on a

7–30-year interval (Hennessy et al. 2005; Clarke et al. 2011). These seasonal and spatial differences in fire risk result from differences in weather. The weather determines the conditions for ignition and spread and the differences in the amount and dryness of fuel sources (Hughes & Steffen 2013).

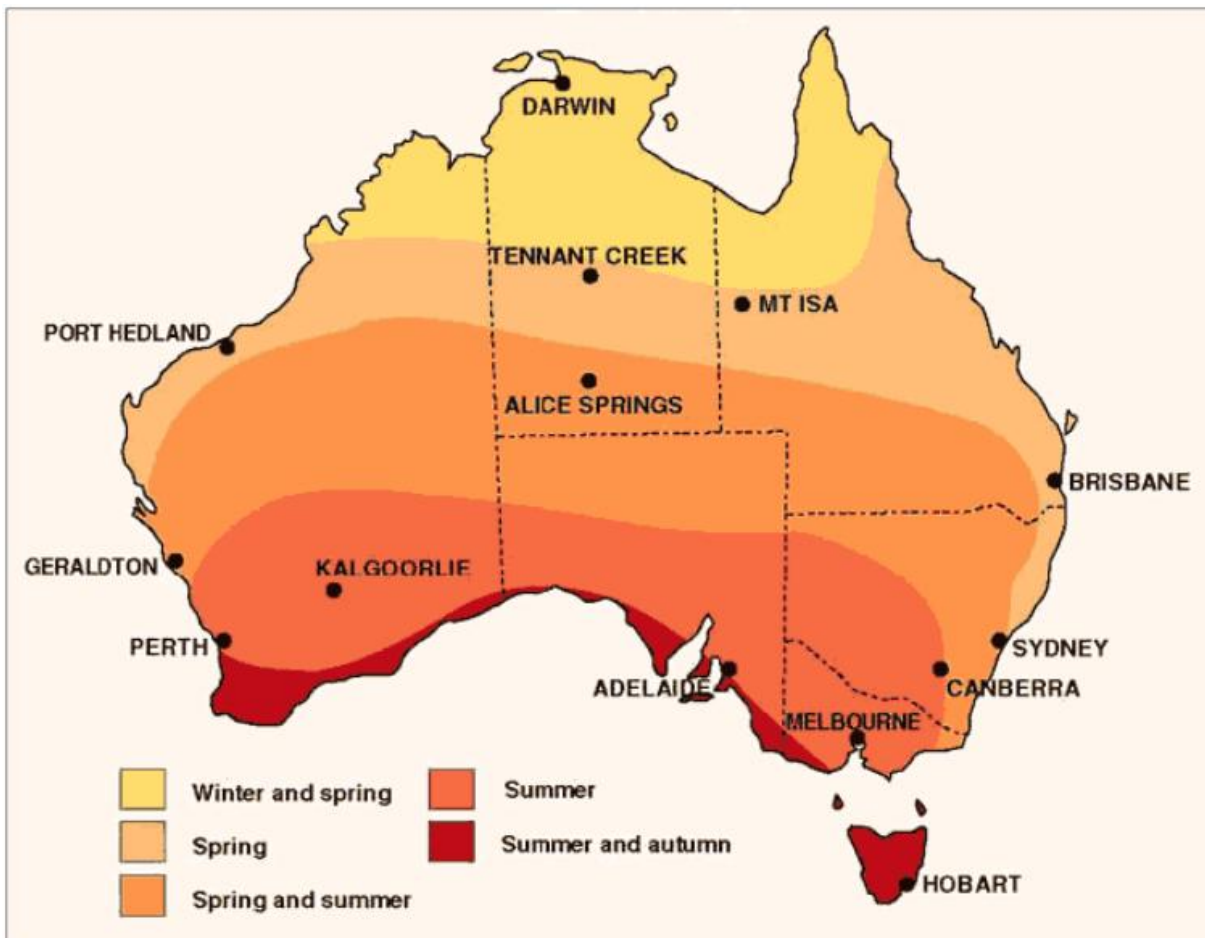


Figure 2.24 Seasonal pattern of fire danger (Hennessy et al. 2005)

Wildfires can have serious social, environmental and economic consequences, including loss of life, physical and mental health impacts, damage to property and infrastructure, and damage to natural ecosystems (Hughes & Steffen 2013). In agricultural and rangeland areas, uncontrolled fire can destroy crops and pastures, damage fencing and other fixed infrastructure, kill livestock and cause smoke damage to fruit and vegetable crops (Hughes & Steffen 2013). It has been conservatively estimated that bushfires directly cost the Victorian agricultural industry \$42 million per year and a total loss to the broader Victorian economy of \$92 million per year (Keating & Handmer 2013 cited in Hughes & Steffen 2013, p. 16).

The relative importance of weather and fuel varies in determining the risk of fire. Fire activity is not limited by the amount of fuel or the weather during the dry season in northern savannas, but it is strongly determined by weather conditions and fuel moisture content in south-west forest areas (Hughes & Steffen 2013).

Fire weather risk is usually quantified using the Forest Fire Danger Index (FFDI) or the Grassland Fire Danger Index (GFDI) (Lucas et al. 2007). These indices positively

correlate with air temperature and wind speed and negatively correlate with relative humidity (Lucas et al. 2007). The FFDI also positively correlates with a 'drought factor' that depends on the daily rainfall and time since the last rain, while the GFDI positively correlates with fuel load and dryness (Lucas et al. 2007). FFDI values are nonlinear and must be interpreted with respect to local baseline values and fire danger thresholds (Table 2.7; Clarke et al. 2012).

Table 2.7 Forest Fire Danger Index and Grasslands Fire Danger Index categories (Hughes & Steffen 2013)

Category	FFDI	GFDI
Catastrophic	>100	>150
Extreme	75–99	100–149
Severe	50–74	50–99
Very high	25–49	24–49
High	12–24	12–24
Low to moderate	0–11	0–11

Current trends

Fire danger has increased across Australia over the last 40 years in response to drier and hotter conditions (Clarke et al. 2012; Hughes & Steffen 2013). Drier conditions have increased the length of the fire season in the south-west of WA (McCaw & Hanstrum 2003). Between 1973 and 2010, cumulative FFDI (annualised fire weather danger) showed a non-significant, increasing trend at Port Hedland, Carnarvon, Meekatharra, Geraldton, Albany and Esperance and a statistically significant trend ($P < 0.05$) at Broome, Perth and Kalgoorlie (Figure 2.25). On a seasonal basis, fire danger increased more in winter and spring than in summer and autumn (Figure 2.26). The frequency of extreme fire events also increased at all of the locations examined, but trends were only significant at Perth, Kalgoorlie and Broome (Clarke et al. 2012). It should be noted that while the trends are consistent with changed fire conditions due to climate change, the magnitude of these trends is generally less than the range of interannual variability over the period (Clarke et al. 2012).

Declining rainfall in the Perth region has been accompanied by an increase in the frequency of extremely dry easterly winds since the late 1970s (Keelty 2011). These winds increase the intensity and the rate of spread of wildfire and prescribed burns, making them more difficult to control and reducing the opportunities for fuel reduction burning (Keelty 2011). Fuel reduction burning is the managed burning of an area of vegetation to create zones of reduced fuel load, to decrease the rate of spread and intensity of wildfires (Fernandes & Botelho 2013 cited in Enright & Fontaine 2013, p. 5).

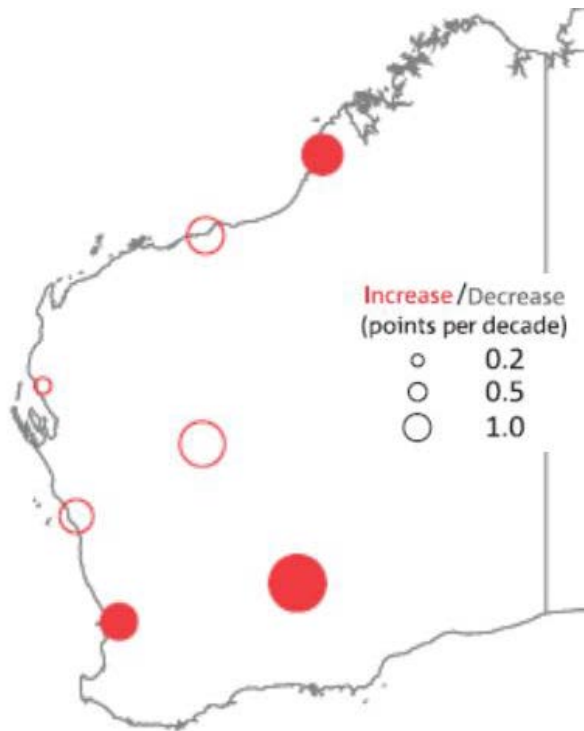


Figure 2.25 Magnitude of annual trends in cumulative FFDI. Filled circles indicate the trend is significant ($P < 0.05$; BoM & CSIRO 2014)

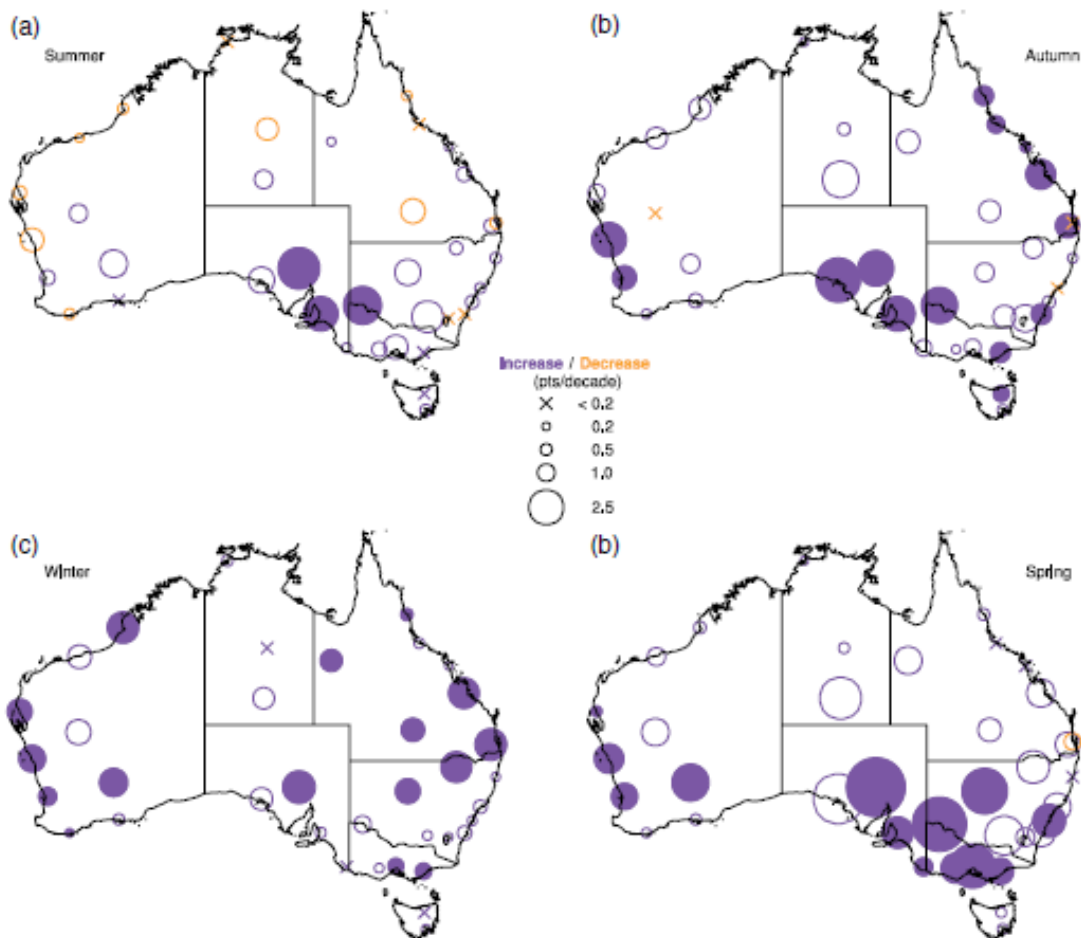


Figure 2.26 Magnitude of seasonal trends in cumulative FFDI. Filled circles indicate the trend is significant ($P < 0.05$; Clarke et al. 2012)

Future projections

Global warming is likely to increase fire frequency and severity (Hennessy et al. 2005; Enright & Fontaine 2013; Hughes & Steffen 2013; Hope et al. 2015). As WA becomes warmer with more and longer hot spells (Figure 2.9 and Figure 2.10), drier (Figure 2.17) and possibly windier in summer (Figure 2.23), fire danger can be expected to increase (Table 2.8) with less time between fires (Keelty 2011; Cary et al. 2012; Hughes & Steffen 2013). Weather conditions will be the greatest driver of altered fire risk with the contribution of fuel load and fuel dryness largely dependent on whether rainfall increases or decreases at a particular location. The Mid West Regional Council, comprising the Carnamah, Coorow, Mingenew, Morawa, Mullewa, Perenjori and Three Springs shires, identified bushfire management as their highest priority climate change risk (Nash et al. 2010).

While detailed projections are lacking for much of WA (Clarke et al. 2012), Williams et al. (2001) found that projected cumulative seasonal fire danger index increased by 20–40% across WA for a climate scenario with atmospheric CO₂ at twice the current level. CMIP5 modelling indicates the number of days with severe fire danger rating and the cumulative FFDI are likely to increase over most of WA in response to increased temperatures and decreased rainfall, except in the Kimberley, where rainfall is projected to remain unchanged or even increase (Table 2.2). The greatest projected increases in severe fire days are in the Pilbara and northern rangelands — 27–331% at Port Hedland and 50–517% at Carnarvon by 2090 under RCP 4.5 and RCP 8.5. The greatest increases in cumulative FFDI are in the northern rangelands and southern coastal areas — 1–79% at Carnarvon and 8–75% at Albany and Esperance (Table 2.2).

Modelling of GFDI in eastern Australia found that while projected climate change increased GFDI, reduced pasture production reduced the fuel load so that fire intensity was largely unchanged (King et al. 2012).

Table 2.8 Potential impacts of increased atmospheric CO₂ and climate change on fire risk factors. Number of asterisks indicates the relative magnitude of impact (Hughes & Steffen 2013)

Atmospheric and climatic change	Fire risk factor	Increased risk	Decreased risk
Increased temperature, more extreme hot days	Weather	*****	
Increased temperature	Fuel condition	*	
Increased temperature	Fuel load	*	*
Decreased rainfall	Fuel condition	**	
Decreased rainfall	Fuel load		**
Increased rainfall	Fuel load	**	
Increased rainfall	Fuel condition		**
Increased incidence of lightning	Ignition	*	
Increased atmospheric CO ₂	Fuel load	*	

3 Climate change mitigation

Summary

- Global mitigation is the best way to avoid the worst effects of climate change.
- There are opportunities for landowners to mitigate agricultural emissions and sequester atmospheric carbon by:
 - generating carbon credits from carbon farming:
 - sequestering carbon in the soil and vegetation
 - reducing emissions from livestock, the soil and burning
 - increasing energy efficiency
 - reducing inputs and the associated embedded energy:
 - undertake life cycle analyses
 - generating renewable energy:
 - use crop residues, processing residues and livestock manures to generate bioenergy or biofuels
 - generate solar or wind power on-farm.
- Land managers must consider the costs and benefits of changing practices to mitigate emissions or sequester carbon.
- Carbon farming activities that return multiple economic and environmental co-benefits are most likely to be economically viable.

Without additional efforts to reduce greenhouse gas emissions, global temperatures are likely to increase by 3.7–4.8°C by 2100. Without mitigation, climate change will significantly affect water resources, coastal ecosystems, infrastructure, health, agriculture and biodiversity (IPCC 2014). Given the potential for high levels of social, economic and environmental disruption that will occur as a result of the worst effects of climate change, mitigating greenhouse gas emissions should be prioritised at the global scale.

Limiting temperature change to less than 2°C will require rapid improvements in energy efficiency. It will also require nearly quadrupling the use of energy technologies like renewables, nuclear, fossil energy with carbon capture and storage, widespread use of bioenergy with carbon capture and storage and a switch to low-carbon transport fuels (Edenhofer et al. 2014; Institute for Sustainable Development and International Relations [IDDRI] 2014).

Cropping and grazing land management and restoration of organic soils have been identified as the most cost-effective agricultural mitigation options at a global scale (Edenhofer et al. 2014; IDDRI 2014).

Nationally, agriculture is responsible for only 15% of greenhouse gas emissions, but the sector is the largest emitter of methane and nitrous oxide (Commonwealth of Australia 2015). Under current accounting rules, emissions generated during the manufacture and transport of agricultural inputs such as fertilisers, herbicides,

pesticides and agricultural machinery are not counted as agricultural emissions, nor are emissions from the fuel used by agricultural vehicles either on-farm or in transporting produce. The fuel used to generate electricity consumed on-farm is also excluded.

Greenhouse gases are emitted from agricultural lands as a result of a number of processes including:

- decay or burning of biomass
- feed digestion by livestock
- addition of nitrogen fertiliser and animal manure to the soil
- return of crop residues to the soil
- nitrogen fixation
- nitrogen leaching and run-off
- atmospheric deposition
- anaerobic decomposition of organic matter during flood irrigation.

Livestock are Australia's largest source of methane and agricultural soils are the greatest source of nitrous oxide (Commonwealth of Australia 2015).

Mitigation options that also deliver adaptive co-benefits can be a cost-effective way of dealing with climate change (Edenhofer et al. 2014). It should be noted that taxing or capping greenhouse gas emissions from sectors of the economy that provide agricultural inputs or services can increase input costs for agricultural businesses. Any mitigation scheme that caps agricultural greenhouse gas emissions and mandates that emissions above the cap be offset would directly increase the cost of agriculture. While these are not immediate risks to agriculture, they should be considered in long-term risk assessment (Thamo et al. 2013).

Australia is a signatory to the Kyoto Protocol, an international agreement aimed at mitigating climate change by reducing global greenhouse gas emissions (United Nations 1998). As part of international efforts, Australia has adopted a number of measures to reduce greenhouse gas emissions and remove (sequester) CO₂ from the atmosphere with the global goal of limiting global warming to less than 2°C. Greenhouse gas emissions by the agricultural sector are not capped in Australia, nor do they have to be mandatorily offset. However, producers and land managers have the potential to benefit financially from reducing carbon pollution by voluntarily undertaking carbon farming projects.

Carbon farming is about changing farming management and practices to reduce greenhouse gas emissions from soil, vegetation or livestock or to remove CO₂ from the atmosphere by storing (sequestering) carbon in vegetation and the soil (Sudmeyer et al. 2014).

In addition to carbon farming, producers can reduce the amount of inputs used in production or change the type of input in ways that can reduce costs and the emissions associated with the embedded energy of the input. For example, soil

testing can reduce the application of inorganic fertilisers and controlled traffic can reduce the amount of chemical, fertiliser and fuel used. Life cycle analyses are a useful tool for understanding the energy inputs required at different stages of the production process and for identifying where changes can be made.

Producers can also generate renewable energy on-farm by using crop residues, processing residues or livestock manures to generate bioenergy or biofuels, or by generating solar or wind power. Renewable energy reduces the need for fossil fuels and in some cases, reduces greenhouse gas emissions from manures or residues that would otherwise rot or be burned.

Anyone considering carbon farming must consider returns on capital, administrative costs and issues pertaining to permanence and land-use change. Given that medium-term carbon prices are likely to be low, offset income alone will not be enough to make most carbon farming projects economically viable. Carbon farming activities need to return multiple economic and environmental co-benefits to be attractive to land managers (Sudmeyer et al. 2014).

4 Climate change and agriculture in Western Australia

Summary

- Climate change will affect average agricultural productivity and inter-annual variability.
- These impacts will vary regionally and by enterprise, with some regions and enterprises benefiting and some not.
 - Reduced rainfall is likely to be a dominantly negative influence.
 - Increased temperature could be beneficial or harmful depending on season and location.
 - Broadacre crop yields may increase in wetter, high rainfall areas and decrease in lower rainfall northern and eastern areas.
 - Some horticultural crops will be adversely affected by increased minimum and maximum temperatures.
 - Decreased water availability is concerning to all farmers but particularly to those irrigating crops.
 - Forage productivity is likely to decline over much of the state, resulting in a greater percentage decline in livestock productivity and profitability.
- Reduced rainfall and climate variability is likely to place severe stress on rangeland enterprises in southern WA.
- Climate change and subsequent changes to agricultural enterprises and practices will alter the distribution and activity of agricultural weeds, pests and diseases.

The previous chapters describe how global atmospheric greenhouse gas concentrations are increasing and outline how the WA climate may be affected as a result. It is projected that WA will become generally warmer, with rainfall declining in western and southern areas but remaining unchanged or increasing in northern and inland areas, and with a greater risk of drought and more-intense storms and tropical cyclones.

IPCC AR5 identifies eight important risks for Australasia during this century, six of which have the potential to directly affect the agricultural sector in WA (Barross et al. 2014):

- increased frequency and intensity of flood damage to settlements and infrastructure, driven by increasing extreme rainfall
- constraints on water resources in southern areas because of rising temperatures and reduced winter rainfall
- increased morbidity, mortality and infrastructure damage during heat waves, resulting from increased frequency and magnitude of extreme high temperatures
- increased damage to ecosystems and settlements, economic losses and risks to human life from wildfires

- increased risks to coastal infrastructure and low-lying ecosystems from continuing sea level rise
- significant reduction in agricultural production in the south-west if scenarios of severe drying are realised.

The following risks can be added:

- reduced average production in areas other than the south-west
- increased year-to-year variability in production
- positive and negative impacts on product quality
- changing location of areas suitable for particular agricultural enterprises, particularly at the margins
- increased risk of some types of land degradation (Howden et al. 2013).

These risks will vary regionally and by enterprise, with some regions and enterprises benefiting and some not.

To understand the possible impacts of climate change, we must rely on modelled projections of climate change and modelled simulations of the expected impact on crops, pasture or livestock, and understand that all of these projections are subject to uncertainties (Yinpeng et al. 2009). Asseng et al. (2013) have shown that the variation in climate change impact across crop models can be greater than the variation in climate projection across global climate models. This variability among models needs to be kept in mind when considering published projections of future crop yields in WA that have been derived almost exclusively using the Agricultural Production Systems sIMulator model (APSiM, see apsim.info/).

Important interactions that are currently not described or poorly described by crop, pasture and livestock models include:

- effects of extreme weather conditions such as frost or hot spells
- climate modification of weed, pest and disease incidence
- uncertainties about the extent and type of future adaptation
- field response of crops and pasture to elevated CO₂ concentration
- interactions of climate and management variables with elevated CO₂ concentration
- effects of altered temperature on the chilling requirements of horticultural crops in WA (Tubiello et al. 2007; Darbyshire et al. 2013c; Challinor et al. 2014; Barlow et al. 2015; Rezaei et al. 2015).

In addition to the ecological pressures of climate change, producers will need to adapt to a suite of other interacting socioeconomic and climate change impacts related to increasing human populations, changing human dietary preferences, increased input costs and policy-related economic pressures, such as land-use pressures and mitigating greenhouse gas emissions (Henry et al. 2012).

While most climate change impacts are likely to be gradual in onset and effect, it is much more difficult to evaluate the likely occurrence and impact of extreme events, or impacts that have thresholds so that a small change in one variable may trigger a major unexpected change in another (Morgan et al. 2008). For example, the increased frequency of heat stress, droughts or floods may adversely affect crops and livestock beyond the impacts of average climate change, creating the possibility for surprises, with impacts that are larger and occur earlier than projected when using changes in average variables alone.

Some of these issues are beyond the scope of this review, so the following sections will focus on the direct impacts of climate change on crop and livestock productivity in WA and the main adaptive responses that have been adopted and are proposed to deal with past and future climate change.

4.1 Agroecological zones and land use

Agriculture in WA contributes more than \$5 billion annually to the state's economy, and occupies about 38% (88.4 million hectares) of the land area (ABS 2013a, 2013d). Livestock grazing is the most widespread land use, occupying about 94% of the agricultural area. Between 2002 and 2007, grain production contributed 54% of the total value of agricultural production in WA; meat production, 21%; horticultural production, 11%; and wool, 10% (Islam 2009). Wheat is the dominant crop and WA is the largest producer and exporter of wheat in Australia (Hertzler et al. 2013).

WA can be broadly divided into five agroecological zones according to climate (Figure 4.1a) and land use (Figure 4.1b):

- Extensive pastoral cattle enterprises, mainly grazing native savanna, occupy the tropical north. These enterprises contribute the largest proportion (29%) of the state's meat cattle herd (ABS 2008).
- Extensive pastoral sheep, goat or cattle enterprises, grazing native shrublands, grasslands and woodlands, occupy the higher rainfall areas of the arid interior.
- Various combinations of broadacre cropping with sheep and cattle, grazing improved pastures on mixed farms occupy the Wheatbelt and Mediterranean environments. Wheat is mainly produced in areas of the Wheatbelt region with less than 500mm of annual rainfall and over 40% of production is from areas receiving less than 325mm. Historically, the Mediterranean region and higher rainfall areas of the Wheatbelt region were used for sheep production. Currently 23% of the Mediterranean region is used for cropping (Hertzler et al. 2013), 17% is used for meat cattle and most of the sheep are in the wheatbelt (ABS 2008).
- Intensive animal production, such as poultry, pigs and feedlots, is mostly located in the Temperate Coast and Mediterranean regions.
- Over half of the horticultural production is from the Temperate Coast region, with smaller irrigation areas at Gingin, Moora, Geraldton, Carnarvon and Kununurra (Ord). Apples are WA's main orchard fruit crop, oranges are the main citrus fruit and carrots and potatoes are the main vegetable crops (ABS 2008). Work is underway to double the size of the Ord River irrigation area and to develop new

irrigation areas using freshwater aquifers south of Broome, in the Pilbara and around Moora.

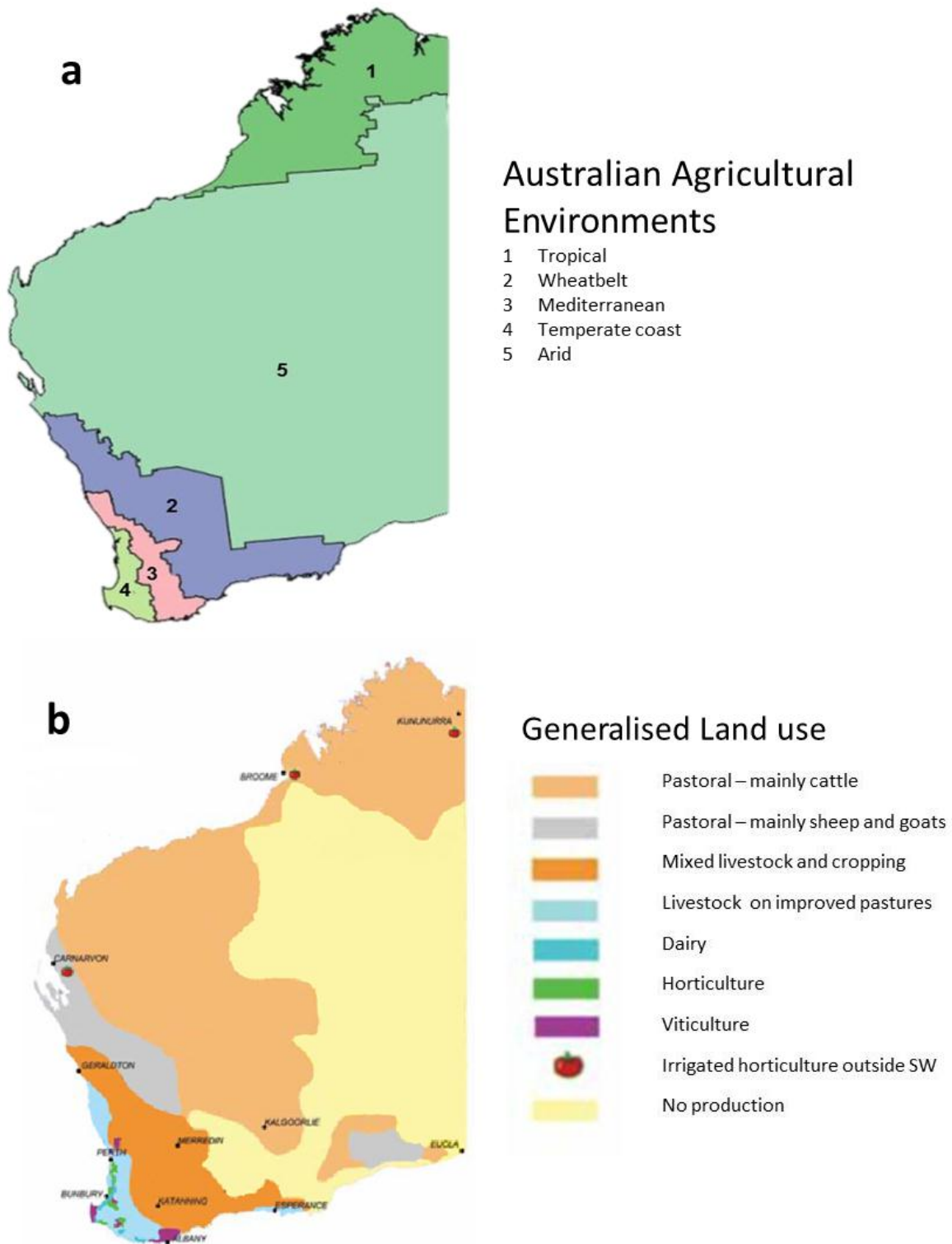


Figure 4.1 (a) Major agroecological zones; and (b) agricultural land uses in WA (ABS 2013a; DAFWA 2012)

4.2 Effects on plant physiology and development

Summary

- The impacts of changing rainfall, temperature, CO₂ and other climatic variables will affect average crop, pasture and horticultural productivity, inter-annual variability, quality and nutrient cycling:
 - reduced rainfall is likely to be a dominantly negative influence
 - increased temperature could be beneficial or harmful depending on season and location
 - there are varietal and species differences in tolerance to temperature stress
 - increased CO₂ concentrations will improve plant water use efficiency
 - increased CO₂ concentrations can reduce the nutritional quality of grains and forages.

The physiological (plant metabolism and function) and phenological (plant development) impacts of changing rainfall, temperature and CO₂ on plant growth are first discussed separately (Chapters 4.2.1, 4.2.2 and 4.2.3) to understand the mechanisms involved and then the combined effect on production is considered in Chapter 4.2.4.

4.2.1 CO₂ concentration

Plants respond to rising atmospheric CO₂ concentration through increased photosynthesis and reduced stomatal conductance of water vapour — the rate at which water vapour passes between the leaf tissue and the atmosphere (Ainsworth & Rogers 2007). This response is sometimes referred to as CO₂ fertilisation. For most plants, current atmospheric CO₂ concentrations limit the rate of carbon fixation by photosynthesis (Rotter & van de Geijn 1999; Hogg & Fangmeier 2008).

As the atmospheric CO₂ concentration increases, the partial pressure of CO₂ within the leaf increases, which allows for greater rates of net leaf photosynthesis and reduced photorespiration (Ainsworth & Rogers 2007; Fitzgerald et al. 2010; Asseng & Pannell 2013; Dias de Oliveira et al. 2013). Greater CO₂ concentrations also allow for the partial closure of stomata, which reduces water loss by transpiration and improves plant water use efficiency (Rotter & van de Geijn 1999; Hogg & Fangmeier 2008). These effects lead to improved performance and yield of plants, even in conditions of mild water stress (Rotter & van de Geijn 1999; Dias de Oliveira et al. 2015).

Because of differing metabolic pathways, increased CO₂ concentrations benefit temperate (C3) species more than tropical (C4) species (Rotter & van de Geijn 1999; Harle et al. 2007; Tubiello et al. 2007; Stokes et al. 2010; Henry et al. 2012). Nitrogen fixing plants also tend to benefit more from enhanced CO₂ concentration where nitrogen availability limits growth (Rotter & van de Geijn 1999).

Increased CO₂ concentrations influence a number of crop yield components, though the response differs among species and cultivars (Fitzgerald et al. 2010). For wheat, root and shoot biomass production is generally increased along with the number of

tillers per plant at maturity (16%), flowering tillers per unit ground area, grain weight (9%) and grain number per ear (6%) (Hogy & Fangmeier 2008; Seneweera et al. 2010; Dias de Oliveira et al. 2013; Benlloch-Gonzalez et al. 2014; Dias de Oliveira et al. 2015). A greenhouse trial in WA found that increased CO₂ concentrations increased the yield of wheat subjected to terminal drought by 24% (Dias de Oliveira et al. 2015). Simulations of wheat in WA using ambient temperature and rainfall and an atmospheric CO₂ concentration of 550ppm, found wheat yield increased by 2–17%, and when the CO₂ concentration was increased to 700ppm, yield increased by up to 38% (Table 2.1 shows when these concentrations are reached under various emission scenarios) (van Ittersum et al. 2003; Ludwig & Asseng 2006). Increasing the rate of nitrogen fertiliser application in conjunction with elevated atmospheric CO₂ concentration resulted in further increased yields (Ittersum et al. 2003; Ludwig & Asseng 2006).

While there is not much published information on the effect of increased CO₂ concentration on fruit trees, it could be expected that photosynthesis will increase, transpiration will decrease and water use efficiency will improve (Reid 2010). Increased CO₂ concentration increases the yield of some vegetable crops but not others (Reid 2010). Generally, where benefits have been found in simulated trials, the actual effect in the field has been less (Reid 2010).

As atmospheric CO₂ concentration increases, the concentration of micronutrients and macronutrients in plant biomass and grains can decline (Rotter & van de Geijn 1999; Hogy & Fangmeier 2008; Dias de Oliveira et al. 2013; Myers et al. 2014). Reducing the nutritional quality of leaf tissue may mean that livestock need to eat more plant biomass if they are to maintain the same level of nutrients in their diet (Rotter & van de Geijn 1999). For cereals, elevated CO₂ concentration promotes grain yield but is likely to reduce grain protein concentrations by 4–14% (Ludwig & Asseng 2006; Hogy & Fangmeier 2008; Erbs et al. 2010; Fitzgerald et al. 2010; Norton et al. 2010; Fernando et al. 2012a and 2012b; Dias de Oliveira et al. 2013).

There are several theories to explain the reduced nutritional quality:

- A dilution effect may result from increased plant growth, where the uptake of minerals and nutrients does not actually decline with elevated CO₂ and in fact, the increased demand may lead to accelerated depletion of these nutrients from the soil (Fernando et al. 2012a and 2012b).
- Nitrogen uptake from the soil may be reduced because of lower transpiration rates resulting from enhanced water use efficiency (Hogy & Fangmeier 2008).
- Nitrate assimilation may be inhibited, which is hypothesised to decrease nitrate absorption by the plant (Fitzgerald et al. 2010).
- Down regulation of plant photosynthetic proteins rather than reduction in nitrogen supply may occur because of changed soil supply processes (Norton et al. 2010).
- Remobilisation of nitrogen to grain could be inhibited during reproductive development (Fernando et al. 2012a, 2012b).

Carbon dioxide-induced reduction in grain protein may not be offset by increased application of nitrogen fertiliser, as more nitrogen fertiliser may translate to higher biomass and yield production rather than enhanced redistribution of nitrogen to the grain (Hogy & Fangmeier 2008).

Protein concentration is important in bread-making because it is positively correlated with baking qualities such as dough strength (Erbs et al. 2010). The concentration of gluten and amino acids in wheat grain protein can also change under elevated CO₂, which will alter the nutritional value of the grain and also affect dough quality (Hogy & Fangmeier 2008). Reduced grain protein may reduce financial returns to producers. However, lower grain protein may benefit the brewing and starch industries (Hogy & Fangmeier 2008, Erbs et al. 2010).

In addition to reduced grain protein, several studies have noted a reduced concentration of mineral nutrients with elevated CO₂ (Erbs et al. 2010; Fitzgerald et al. 2010; Fernando et al. 2012a, 2012b). Fernando et al. (2012b) suggest the effect is greater in low rainfall, Mediterranean cropping systems. The most prominent effect of elevated CO₂ on mineral composition of wheat and barley is the significantly reduced sulfur concentration (Erbs et al. 2010).

4.2.2 Temperature

Temperature is the fundamental environmental parameter controlling plant development (Anderson & Garlinge 2000). The temperature requirements for many crops are broad and vary depending on crop phenological stage, species (Table 4.1) and cultivar (Figure 4.2; Reid 2010). There are temperature thresholds above which crop yield and/or quality may be reduced (Reid 2010). These thresholds also vary between crops and cultivars. For example, lettuce quality can decline when maximum temperatures exceed 24–28°C, while tomatoes and bananas are more tolerant and only suffer heat stress at temperatures above 29–35°C and 38°C, respectively (Deuter et al. 2012a; Deuter et al. 2012b; Deuter et al. 2012c; Webb & Whetton 2010). For wheat, leaf area growth and photosynthesis are greatest when daily mean temperatures are 11–24°C and 17–19°C, respectively, and leaf senescence — the process of ageing — increases threefold when maximum temperatures exceed 34°C (Asseng et al. 2010).

Many crops have vernalisation — breaking dormancy — requirements related to day length and/or time below a critical temperature (chilling). For fruit crops, inadequate chilling can result in prolonged or uneven dormancy break, leading to reduced fruit yield and quality (Webb & Whetton 2010).

Phenological development is a function of time and temperature (day degrees) and accelerates at higher temperatures, with an upper limit (Rotter & van de Geijn 1999). Most plant processes double in rate for every 10°C increase in temperature between 0°C and 30°C (Anderson & Garlinge 2000). For wheat and grapes, their optimal growing temperatures are greater than the current average growing season temperature of 10–12°C during winter for wheat and 13–17°C during spring–autumn for grapes (van Gool & Vernon 2005; Ward 2009). Therefore, any increase in growing season temperature may increase growth rates and reduce development time.

Table 4.1 Optimal growing temperatures and temperature threshold above which yield declines for various horticultural crops (Maynard & Hochmuth 1997 cited in Rogers 2013, p. 80)

Crop type	Optimal temperature range for growth (°C)	Upper threshold (°C)
Chilli	21–30	35
Eggplant	21–30	35
Babyleaf – rocket	16–24	32
Capsicum	20–25	32
Cauliflower	15–18	32
Cucumber	18–24	32
Pumpkin	18–24	32
Sweet corn	24–30	32
Zucchini and butter squash	18–24	32
Broccoli	15–18	30–32
Babyleaf – spinach	15–18	30
Carrot	15–18	30
Garlic	13–24	30
Leek	13–24	30
Shallot	13–24	30
Tomato	18–24	29
Bean	15–21	27
Beetroot	15–18	27
Artichoke	15–18	24
Babyleaf – chard	15–18	24
Brussels sprout	15–18	24
Cabbage	15–18	24
Celery	15–18	24
Herbs	15–18	24
Lettuce – cos	12–21	24
Lettuce – fancy and babyleaf	12–21	24
Lettuce – iceberg	12–21	24
Parsnip	15–18	24
Pea	15–18	24
Silverbeet	15–18	24
Snow pea and sugar snap pea	15–18	24
Swede and turnip	15–18	24

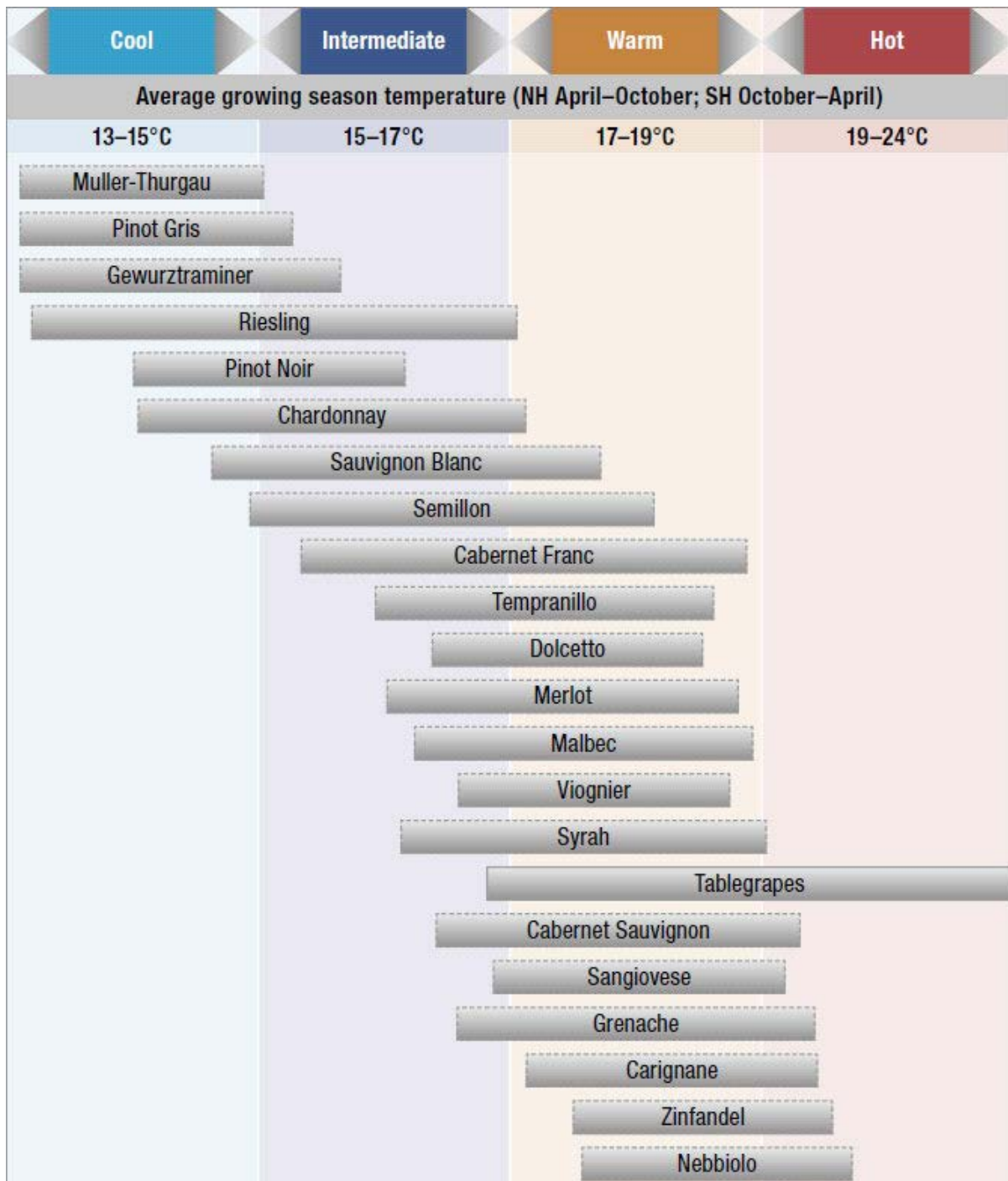


Figure 4.2 Average growing season temperatures in the world's benchmark regions for various grape vine varieties (Ward 2009)

However, if vegetative and reproductive growth stages are shortened, less radiation is intercepted which can result in lower biomass production and grain yield (Ludwig & Asseng 2006; Dias de Oliveira et al. 2013; Asseng et al. 2010). Warmer conditions and accelerated development can also be beneficial or harmful depending on whether the crop is exposed to increased frost or high temperature risk during critical growth phases.

For grain crops, accelerating phenology can shift the grain-filling period to earlier in the season when soil moisture may be more available, thus increasing the harvest index (Ludwig & Asseng 2006). However, increased biomass growth and associated transpiration rates can also increase crop demand for water later in the season (Dias de Oliveira et al. 2013; Rotter & van de Geijn 1999). The actual impact of temperature on grain yield is influenced by season length and soil type.

The optimum flowering time or 'flowering window' is a balance between the risk of frost damage if flowering occurs too early in the growing season, and high temperatures and drought experienced if flowering occurs too late. It is important that crops flower in the 'window' if they are to have the best chance of achieving their potential yield. The rate of yield reduction for crops flowering after the optimum time is greatest in the warmer, shorter season environments of the northern and eastern wheatbelt, and least in the cooler, wetter and longer season environments of the south coast (Anderson & Garlinge 2000; Ludwig & Asseng 2006).

A study of global wheat production using an ensemble of 30 crop models with ambient rainfall and atmospheric CO₂, found that global wheat yield would decline by 6% for every 1°C increase in global average temperature (Asseng et al. 2015). Modelling of wheat yields in WA highlights the importance of water availability in moderating the effects of higher temperatures. Wheat yields with 2–4°C higher average temperatures, and ambient CO₂ and rainfall were projected to increase on all soil types in high rainfall areas of WA and decrease on soils with low plant available water in low rainfall areas (van Ittersum et al. 2003; Ludwig & Asseng 2006). Increasing application rates of nitrogen fertiliser in conjunction with elevated temperatures resulted in decreased yields because it increased water use early in the season and thus increased water deficits later (van Ittersum et al. 2003).

Temperature during crop ripening can also affect grain or fruit quality. As temperatures increase (at ambient rainfall and CO₂), the concentration of monounsaturated oils increases and polyunsaturated oils decrease in canola grain (Schulte et al. 2013). Wheat kernel size can decrease by 2–7% for every 1°C increase in temperature (Asseng et al. 2010). Higher temperature can reduce the sugar and vitamin C content of pome fruit and increase the sugar content of grapes (Ward 2009; Reid 2010; Web & Whetton 2010).

Temperature extremes

Temperature extremes can affect crop growth and yield, with low temperatures increasing frost risk during flowering and high temperatures increasing the risk of damage to ripening fruit or developing grain. As for optimal temperature requirements, there are significant differences in tolerance to heat stress among species and cultivars (Table 4.1; Gouache et al. 2012; Talukder et al. 2014).

The frequency of hot spells is forecast to increase over the next 50 years. If this increases the number of extreme heat days during flowering and grain filling, the impact is likely to be negative (Rotter & van de Geijn 1999; Asseng & Pannell 2013). Asseng et al. 2013 state that each day with temperatures over 35°C during grain filling may reduce wheat yield by 5%. This estimate may be an underestimate

because an Australian field trial found that a single day of heat stress (35°C maximum) either near flowering or at early grain fill, reduced wheat yield by 13–25% (Talukder et al. 2014). Wardlaw and Rigney (1994 cited in Asseng et al. 2010, p. 2) estimated that heat stress during anthesis reduced Australian wheat yields by 10%. Asseng et al. (2010) found that at Cunderdin and Dalwallinu, the frequency of days during the wheat grain-filling period with maxima above 34°C would increase by one day for each 1.6°C increase in maximum temperature. For each additional day with maximum temperature above 34°C, yield would decline by 5%.

Temperatures above 32°C during canola flowering can cause flower abortion. High temperatures and low soil moisture during pod development can reduce oil concentration by 3–5% (Vernon & van Gool 2006a).

High temperature events can cause severe fruit loss either by direct damage (sunburn) or by affecting how well fruit can be stored. Temperatures over 35–38°C can cause fruit drop, sunburn on fruit and prevent external colour development (Reid 2010). The temperature at which grape bunches ripen is critical to fruit quality. In hot, dry conditions, sugars become concentrated, acid (malic) is depleted, red colour is lost, phenolics — chemical compounds that give wines their characteristic taste and colour — may not mature and aromas become ‘jammy’ (Ward 2009). As with most other temperature effects, there are varietal differences in critical bunch-zone temperature — for example, critical bunch-zone temperature is 26°C for Pinot Noir and 35°C for Shiraz (Ward 2009).

Temperatures above 30°C will suppress growth of most brassicas — plants in the cabbage family — but for some varieties, this threshold is as low as 25°C, with yield reduced by 6% for every 1°C increase in temperature above the threshold (Reid 2010). Temperature is critical to carrot quality. At temperatures above 21°C, the roots tend to be short and below 16°C they tend to be long. Carotene content declines at temperatures above 25°C or below 16°C, and above 30°C, foliage growth reduces and strong flavours develop in the root (Reid 2010).

Crops are at risk of frost damage when air temperature falls below 2.2°C (Anderson & Garlinge 2000). Again, there are species and varietal differences in frost susceptibility. For example, canola and oats are much more tolerant of frost damage than barley, and barley is slightly more tolerant than wheat. Wheat plants are susceptible to frost damage from ear emergence to the hard dough stage. These stages of development often coincide with frost in September and October in WA (Anderson & Garlinge 2000). In WA, the frost window has broadened slightly and now occurs about three weeks later than before the 1960s (Crimp et al. 2012). These changes in timing of frost incidence are influencing the optimum sowing time of crop varieties.

Frost can damage semi-dormant flower buds in fruit trees and reduce flower intensity in spring. Frost can eventually result in fruit damage and shedding and can damage flowers during spring (Ward 2009; Reid 2010).

4.2.3 Rainfall

Water is generally the most limiting factor in WA dryland cropping systems (Grains Research and Development Corporation 2009; CSIRO 2011). Grain yield directly correlates with growing season rainfall. For example, wheat yield potential increases by 20–22kg/ha for every millimetre of additional rainfall (French & Shultz 1984; Grains Research and Development Corporation 2009). Consequently, reductions in growing season rainfall can reduce potential yield. Under most circumstances, changes in seasonal rainfall distribution and intensity matter more than changes in annual precipitation and evaporation (Rotter & van de Geijn 1999).

Dry autumn conditions can delay sowing and limit potential yield. Dry spring conditions can limit water available for grain filling and result in small, pinched grain because plants are unable to translocate all of their stored starch into the grain. Dry autumn and spring conditions can have a greater effect on grain yield than reduced rainfall in winter, when rainfall is usually in excess of evapotranspiration. However, reduced autumn and spring rainfall is less critical where excess rainfall is stored in the soil and is subsequently available. Canola is regarded as being less tolerant of water deficit than other grain crops.

Simulated wheat yields at low rainfall sites in WA generally decline as rainfall declines. In high rainfall areas, waterlogging can limit yield in some years and average yields initially increase for rainfall reductions up to 20% then decline when reductions exceed 20% (Ludwig & Asseng 2006).

Horticultural crops generally rely on irrigation for some or all of their water requirements. Additional irrigation can make up for declining rainfall where irrigation water supplies are available. However, it is expected that declining rainfall and associated reductions in surface water run-off and groundwater recharge will result in a decline in the availability of irrigation water in many areas.

4.2.4 Integrated effect of CO₂, temperature and rainfall

While the physiological effects of temperature and water availability on crop growth and development are relatively well understood, the effects of CO₂ concentration are less well understood and the interacting effects of these climate variables with edaphic — site physical characteristics — and management variables even less so (Tubiello et al. 2007). Consequently, many studies have concentrated on the effects of increased temperature and reduced rainfall on crop yield in the absence of any other climate change variables. These studies generally project that higher temperatures will improve crop productivity in the cooler and higher rainfall western and southern areas, but higher temperatures and lower rainfall will reduce crop yields over much of the rest of the wheatbelt. In all cases, the magnitude and sometimes the sign of the change depends on soil type and location (van Gool & Vernon 2005, 2006; Vernon & van Gool 2006a, 2006b; Ludwig & Asseng 2006; John et al. 2005; Potgieter et al. 2013). However, increased CO₂ concentration can offset some of the negative effects of increasing temperature and decreasing rainfall. The interacting effects of altered temperature, rainfall and CO₂ concentrations combined with variable physiological responses among species (AbdElgawad et al. 2015) means

that only those studies that include all three climate variables are considered in detail in the following discussion of climate change impacts.

Several studies have suggested a positive relationship between elevated CO₂ and increased atmospheric temperature on crop production up to a critical temperature increase of about 2°C (Rotter & van de Geijn 1999; Dias de Oliveira et al. 2013). However, a more recent meta-analysis of more than 1700 simulation studies from around the world showed that average wheat and maize yields will decline with temperature increases of less than 2°C in temperate and tropical areas, while rice yield will decline at temperature increases above 2°C in the tropics (Challinor et al. 2014). Wheat grown in a greenhouse with CO₂ concentrations of 550ppm and ambient temperature showed increased root and shoot biomass, but there was no change in biomass growth when temperature was increased by 3°C (Benlloch-Gonzalez et al. 2014). Raupacht et al. (2013) found a similar result when they modelled net ecosystem primary production for Australia and found that increasing the CO₂ concentration by 100ppm offset the negative effects of increasing temperature by 1.5°C, but primary production remained strongly linked to rainfall. Greater warming led to disproportionately larger reductions in net ecosystem primary production because of nonlinearities in responses (Raupacht et al. 2013). The meta-analysis of Challinor et al. (2014) found global wheat, maize and rice yields declined (on average) by 0.53% for every 1% decline in rainfall, declined by 4.9% for every 1°C increase in temperature and increased by 0.06% for every 1ppm increase in atmospheric CO₂ concentration. Another analysis of global wheat, maize and rice yields during 1967–2007 found that yields declined by 6–7% for every 1°C increase in seasonal average temperature (Lesk et al. 2016).

Greenhouse experiments with wheat in WA showed increased atmospheric CO₂ concentrations and increased temperature (up to 3°C) can increase yield and partially offset the effects of terminal drought (Dias de Oliveira et al. 2013; Dias de Oliveira et al. 2015). However, at temperature increases greater than 2°C, increased CO₂ concentrations only maintain yields in well-watered conditions and do not offset the effects of terminal drought (Dias de Oliveira et al. 2013).

4.3 Climate change and broadacre crop yields

Summary

Effects of historical climate change:

- Improvements in technology, agronomy and cultivars have effectively increased the rainfall use efficiency of wheat at a greater rate than rainfall has declined in WA.
- During the last 50 years:
 - 50ppm increase in atmospheric CO₂ increased wheat yield by 2–8%
 - 0.8°C increase in average temperature benefited crops during the winter months as accelerated maturity and increased CO₂ concentration offset the increased frequency of hot days during grain filling
 - reduced rainfall had relatively little effect on yield because much of the reduction occurred during winter when rainfall exceeds plant demand and the excess rainfall is effectively lost to the plant anyway.

Effects of projected climate change:

- Projections of future crop yield are constrained by the limitations of climate models and need to consider the combined effects of increased temperature and CO₂ concentration and any changes to rainfall amount and seasonal distribution:
 - technology and management improvements are not accounted for in most models
 - extreme weather events are not captured in most crop modelling.
- Yields decline in drier eastern and northern areas and are largely unchanged or increase in wetter western and southern areas:
 - yield is most affected by changes in rainfall, particularly its timing
 - increased CO₂ offsets some of the negative effects of increased temperature and decreased rainfall
 - higher temperatures, and to a lesser extent declining rainfall, will hasten development times and reduce the flowering period
 - plant available water capacity of the soil becomes increasingly important in determining yield, so yield declines are greater on clay soils compared to sands in eastern areas
 - increased risks are associated with climate variability in drier, marginal areas.

This section describes how Australian crop yields have changed over the last few decades and how they may change in the future. Much of the research relevant to WA has focused on wheat, reflecting its relative importance as a broadacre crop by area sown and by value. The response of wheat to climate change can be interpreted as a broad representation of other commonly grown broadacre crops.

4.3.1 Current trends

Between 1900 and 2000, average wheat yields in Australia increased from around 0.5 tonnes per hectare (t/ha) to nearly 2t/ha in response to improved varieties and management practices (Figure 4.3a). The plateauing in the rate of yield increase since the end of the 1990s has been attributed to the millennium drought in eastern Australia (Kirkegaard & Hunt 2010), reduced growth in public investment in agricultural research and development (Australian Bureau of Agricultural and Resource Economics [ABARE] 2010) and long-term soil degradation (Turner et al. 2016). In WA, average wheat yields have doubled over the last 30 years (Figure 4.3b), but show an increase in yield variability and a similar plateauing in the rate of yield increase since the end of the 1990s. Wheat yield trends have not been uniform across the wheatbelt. Yield increases were greatest in southern and northern areas and least in central and eastern areas, while yield variability was greatest in eastern and northern areas (Figure 4.4).

There is evidence that warmer and drier conditions in recent times are affecting native vegetation and crops at local and global levels. During the period 2000–2011, the net primary production of native woody vegetation in the south-west of WA declined over 15% of its area, with the greatest changes in the north-west and south-east of the region (Brouwers & Coops 2016). Lesk et al. (2016) found that between 1967 and 2007, North American, European and Australian wheat production declined by 20% during drought years and that increasing drought severity increased the global average production loss during drought from 7% in 1964–84 to 14% in 1985–2007.

The increases in WA wheat yields since 1980 are attributed to the adoption of technological and management improvements, such as zero till, soil amelioration, stubble retention, early sowing and better weed control (Turner et al. 2011; Kirkegaard et al. 2011; Asseng & Pannell 2013; Norwood 2015). These changes effectively increased the water use efficiency of wheat at a greater rate than rainfall declined over the period (Figure 4.5). The reduced rate of increase in water use efficiency since 2000 may be because producers are reducing their inputs (risk) in response to climate conditions. Consequently, water use efficiency is lowest in more marginal and variable areas where producers are most conservative in their farming practices and their use of inputs (Figure 4.6; Norwood 2015).

Because yield changes due to improved technology and farming systems were greater than, and effectively masked, any effect of climate change over this period, Asseng and Pannell (2013) used APSiM to estimate the changes in potential yields caused by past climate change. They found that the 50ppm increase in atmospheric CO₂ over the last 50 years would have increased yields by 2% at Mullewa and 8% at Katanning. The 0.8°C increase in average temperature over the period also benefited crops during the winter months. While the frequency of hot days during grain filling increased, the harmful effects of increased temperature were offset by accelerated maturity and the benefits of increased CO₂ concentration. Reduced rainfall was considered to have had relatively little impact, because much of the reduction occurred during winter when rainfall exceeds plant demand and the excess rainfall is

effectively lost to the plant and so does not contribute to yield (Ludwig et al. 2009; Asseng & Pannell 2013).

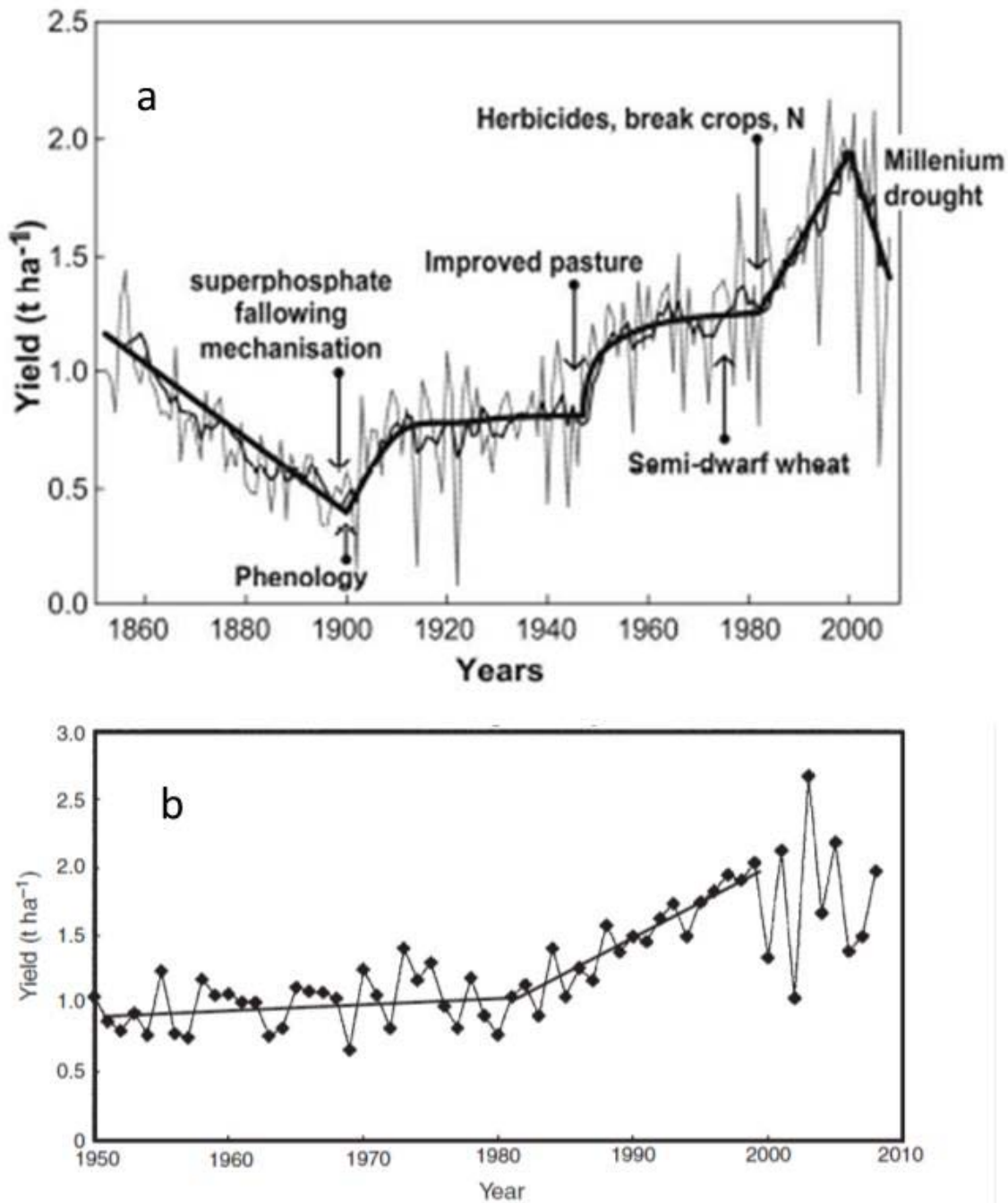


Figure 4.3 Average wheat yield across (a) Australia and (b) WA, with the 10-year moving average (bold line). Approximate timing of adoption of selected management and breeding innovations are shown (Kirkegaard & Hunt 2010; Turner et al. 2011)

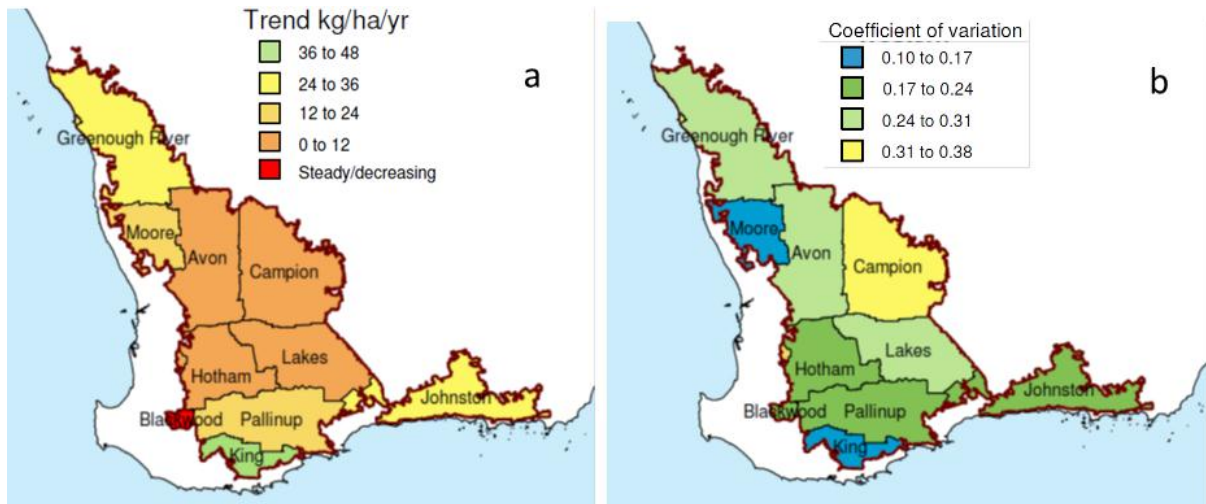


Figure 4.4 Regional trend for (a) wheat yield and (b) variability between 1998 and 2012 (Australian Export Grains Innovation Centre 2015)

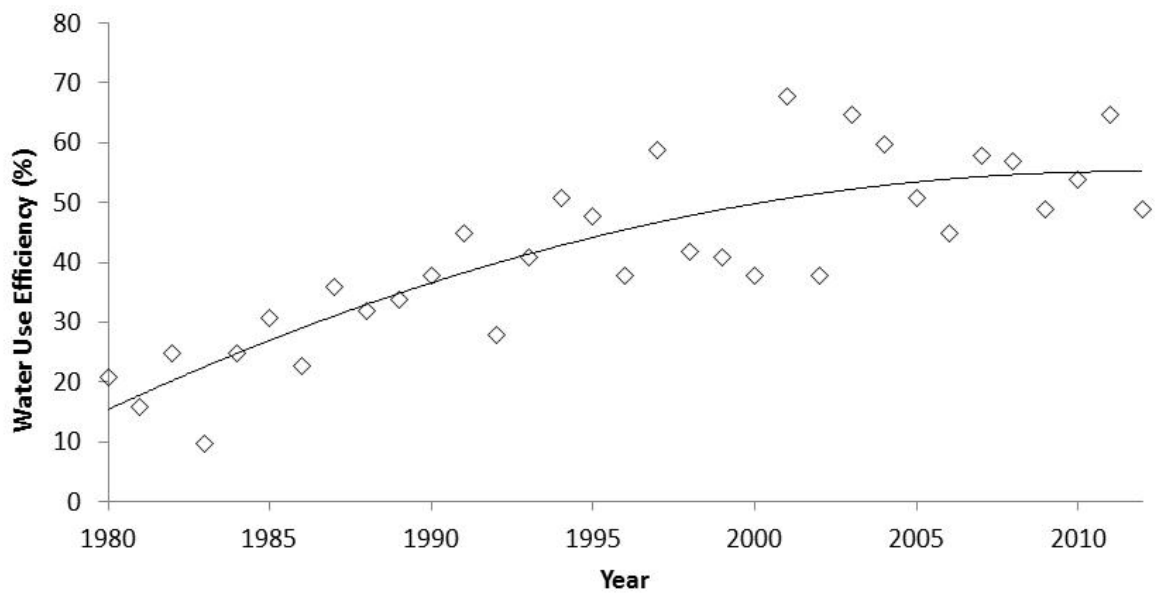


Figure 4.5 Average annual water use efficiency of wheat grown in WA. The fitted line shows the trend in water use efficiency from 1980 to 2012 (after Norwood 2015)

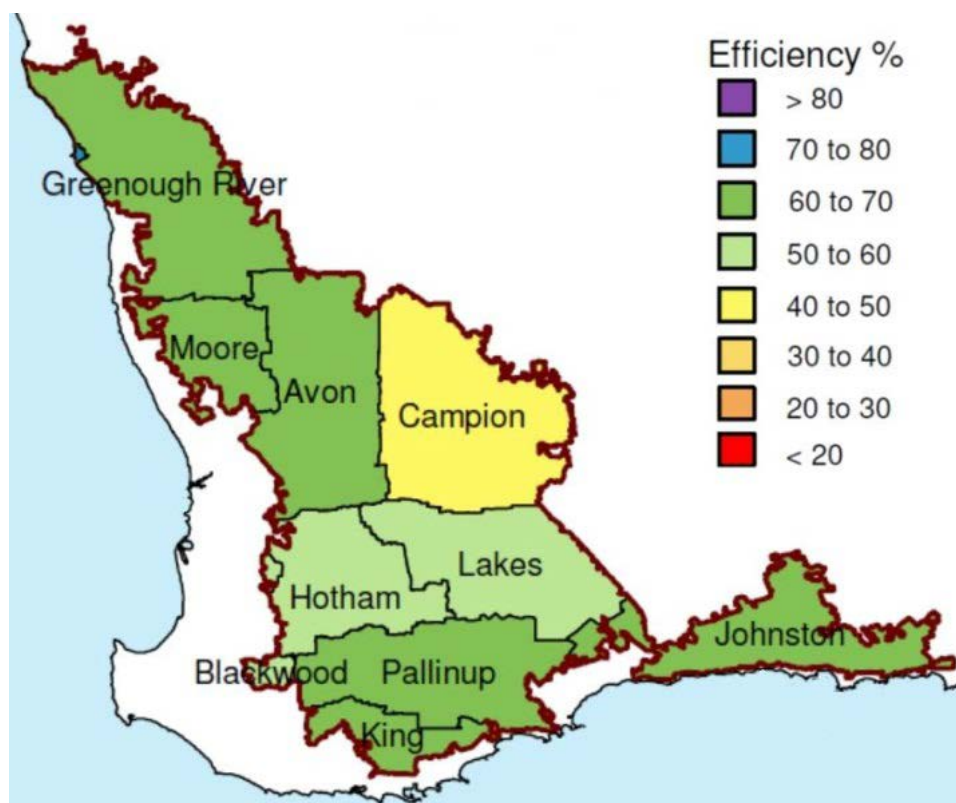


Figure 4.6 Average water use efficiency of wheat in WA (Australian Export Grains Innovation Centre 2015)

4.3.2 Future projections

Any assessment of future changes in agricultural profitability is constrained by the uncertainties within climate and crop models. Future rainfall (amount and seasonal distribution) has greater uncertainties than temperature change. Modelling shows that crop yield is more likely to be affected by changes in rainfall than changes in temperature (Anwar et al. 2015). Additionally, rainfall distribution is likely to have a greater effect on crop yield than absolute reductions, with crop yields being more sensitive to reduced rainfall during May or August than June and July (Ludwig et al. 2009). An increased incidence of false and late breaks (beyond May) is a potential impact on cropping in the central and parts of the wheatbelt (Carmody 2010a; Carmody et al. 2010b). It is important to note that crops are more sensitive to reduced rainfall early and late in the growing season, because the greatest reductions in rainfall are projected for winter and spring (Figure 2.15) and the greatest increase in temperature is projected for spring (Figure 2.9) when crops are flowering and filling grain.

The studies discussed below all used the APSiM model and accounted for future changes in rainfall, temperature and CO₂ concentration. The model uses a daily time step to simulate grain yield based on weather data, soil type (nutrient and plant available soil water content) and crop management (nutrition and time of sowing). It does not consider weeds, pests or diseases, or improvements in technology and management over time. Asseng et al. (2013) showed that the variation in climate change impact among crop models could be greater than the variation in climate

projection across global climate models. To improve confidence in modelled results, they suggested using a suite of crop models to predict yield (Asseng et al. 2013; Asseng et al. 2015). Accordingly, the yield changes discussed below should be regarded as indicative rather than absolute.

Farre and Foster (2010) simulated wheat yield in 2035–64 with an atmospheric CO₂ concentration of 440ppm, a temperature increase of approximately 1°C and a 5–10% rainfall reduction. They found reduced wheat yields over large areas of the wheatbelt (Figure 4.7) with greater yield reductions on clay soils compared to sandy and duplex soils (Figure 4.8). Potential wheat yields were increased in higher rainfall western and far south-eastern areas because of CO₂ fertilisation and reduced risk of waterlogging on duplex soils. Simulations showed an increase in the frequency of years with low or very low yields and a decrease in the frequency of years with high yields at most locations in the low and medium rainfall zones. These yield changes would make cropping a more risky business than it currently is in these locations.

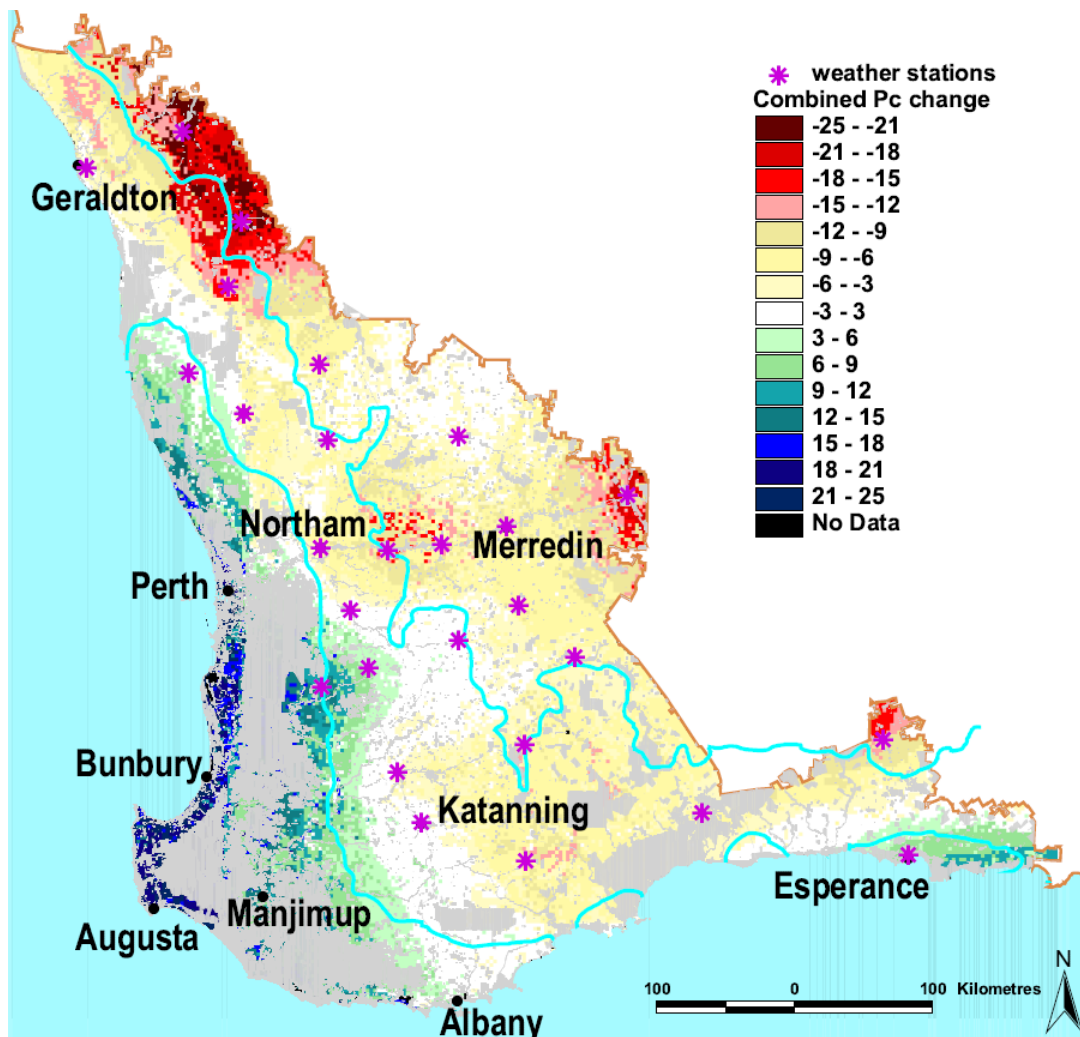


Figure 4.7 Percentage change in simulated wheat yield under a future climate with an atmospheric CO₂ concentration of 450ppm and rainfall reduced by 5–10%, compared to 1975–2004 conditions. Combined yield change, adjusted for the proportion of sand, clay or duplex soils and accounting for area of state forest and reserves (I Farre and D van Gool 2013, pers. comm., 21 November)

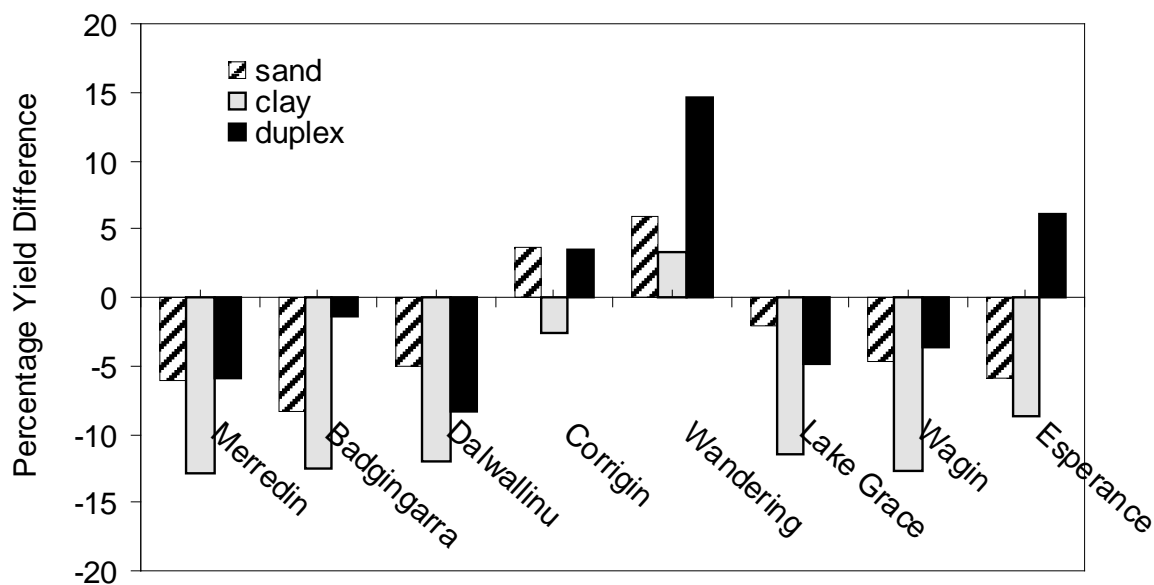


Figure 4.8 Change in simulated wheat yield under a future climate with an atmospheric CO₂ concentration of 450ppm and rainfall reduced by 5–10% compared to 1975–2004 conditions at eight locations in WA with sand, clay or duplex soils (Farre & Foster 2010)

Van Ittersum et al. (2003) found that wheat yields on clay soil decreased by 11% at Moora, 27% at Wongan Hills and 46% at Merredin, with a CO₂ concentration of 550ppm, a temperature increase of 3°C and a rainfall decrease of 25%. On sandy soil, the yield increased by 29% at Moora, was unchanged at Wongan Hills and reduced by 23% at Merredin. Van Ittersum et al. (2003, p. 270) concluded that:

...this may make wheat production unprofitable in large areas of low precipitation regions (e.g. Merredin). Such a finding might imply a possible contraction of the WA wheatbelt under potential future climate change scenarios, or a possible migration of grain growing areas towards the coast. In contrast, in some conditions (high precipitation sites and sandy soils) crops may benefit from a decrease in precipitation, due to a decrease in nitrate leaching.

Ludwig and Asseng (2006) showed that for a high-emission scenario, wheat yields were unchanged for sandy soils, but increased by about 1.5t/ha on clay soils at a higher rainfall site (Kojonup), and decreased by 0.3–1.0t/ha for sandy and clay soils at lower rainfall sites (Binu and Kellerberrin). The high-emission scenario was based on a CO₂ concentration of 700ppm, a temperature increase of 4°C and a 30% reduction in rainfall (2060–70 for SRES A1F1 or A2 scenario, see Table 2.1 for an explanation of scenarios). For an intermediate-emission scenario in 2050 — 525ppm CO₂ concentration, 2°C temperature increase and a 15% reduction in rainfall — wheat yield increased by 0.3–0.9t/ha at the high rainfall sites, was unchanged on sandy soils and slightly decreased on clay soil at the low rainfall sites.

Kingwell and Abadi (2014) found that the cost of producing and supplying cereal straw as a biofuel would decline slightly in the high rainfall, south-western area of the

wheatbelt because the projected yield increases in this area (Figure 4.7) would reduce haulage distances.

Anwar et al. (2015) used downscaled data for future climate under an SRES A2 scenario (see Table 2.1 for an explanation of scenarios) to model wheat, barley, lupin and field pea phenology and growth at Cunderdin, Katanning and two Victorian sites. Under this scenario, annual temperature increases of 1.0°C, 2.0°C and 3.5°C and annual rainfall decreases of 9%, 16% and 26% in 2030, 2060 and 2090, respectively, were used. The models suggested that the time taken for all crops to flower and mature and the length of the flowering period would progressively decline in future. The changes in development rates were greater for cereals and field pea compared to lupin and canola, and greater at cooler, wetter sites compared to warmer, drier sites. Crop yield significantly correlated to rainfall, with proportionally greater reductions in low rainfall environments — wheat yield declined by 0.5% at Katanning and 0.9% at Cunderdin for every 1% decline in rainfall. Field pea, canola and lupin were more affected by declining rainfall than cereals.

Some common themes emerge from these studies:

- Increased CO₂ concentrations will offset some of the negative effects of increased temperature and decreased rainfall.
- Higher temperatures, and to a lesser extent declining rainfall, will hasten development times and reduce the flowering period.
- Crop yield will be most affected by changes in rainfall and particularly the timing of rainfall.
- Technology and management improvements are not accounted for in the models used.
- It is likely that a proportionally greater decline in crop yield will occur in drier eastern and northern areas.
- Crop yields may be largely unchanged or increase in wetter western and southern areas.
- The plant available water capacity of the soil will become increasingly important in determining yield, so yield declines will be greater on clay soils compared to sands particularly in drier in eastern areas.
- The risks associated with cropping in drier, marginal areas will increase.

4.4 Climate change and livestock production

Summary

- In the higher rainfall areas of the south-west, increased temperature in winter and early spring and reduced waterlogging could benefit livestock production by:
 - increasing forage production
 - reducing livestock feed requirements (lower energy maintenance costs)
 - increasing survival of young animals or shorn sheep during cold and wet periods.
- In warmer areas of the state and during the summer months, increased temperatures could negatively affect livestock production by:
 - heat stress reducing forage growth or length of growing season
 - heat stress reducing livestock growth, reproductive success and milk production
 - increasing livestock water requirements (also reduced water quality)
 - increasing livestock exposure and susceptibility to parasites and disease.
- Reduced rainfall and higher temperatures could reduce forage production by up to 10% over the agricultural areas and southern rangelands and 10–20% over the rest of the state
 - the percentage decline in livestock productivity and profitability likely to be greater than the decline in pasture growth
 - inter-annual variability in pasture production is likely to increase
 - rainfall decline and continued climate variability is likely to place severe stress on rangeland ecosystems, grazing enterprises and rural communities in southern WA.
- Increased CO₂ concentrations could reduce pasture digestibility and protein content if C₄ plants became more dominant, but this reduction may be offset by increased growth rates of leguminous species.
- Greater rainfall intensity associated with tropical cyclones may increase encroachment of woody plants into pastoral grasslands.

Livestock producers will need to adapt to a suite of interacting climate change impacts:

- ecophysical changes such as higher temperatures, changes in rainfall distribution and amount and more frequent drought (see Chapter 2)
- economic pressures related to increasing human populations, changing human dietary preferences and increased costs of animal feed
- policy-related economic pressures, such as land-use pressures, mitigating greenhouse gas emissions and increased energy prices (Henry et al. 2012).

The effects of climate change will vary regionally and by enterprise, with some regions benefiting and some not.

While increasing temperature and declining rainfall are likely to provide the greatest ecophysical challenges (Howden et al. 1999), climate change presents producers with five important management issues (Black et al. 2008; Stokes et al. 2010; Henry et al. 2012):

1. forage productivity and quality — vegetation composition, weeds, fire management
2. water quality availability and demand
3. soil degradation
4. animal husbandry and health
5. mitigation — potential to earn offset credits in voluntary carbon framing activities and potential costs if livestock are included in future greenhouse gas emission reduction schemes.

Issues 1, 2 and 4 are discussed in more detail below.

4.4.1 Forage productivity and quality

Livestock performance depends on the quantity and quality (energy content, protein and digestibility) of the feed supply. For broadacre farms, pasture quality largely equates to pasture composition and the availability of young digestible forage, which is, in turn, dependent upon the number of pasture growing days (Stokes et al. 2010).

Climate change will affect the average amount of forage produced, how it varies between years, forage quality, nutrient cycling and species composition and the frequency and intensity of fire (McKeon et al. 2009). However, rainfall is likely to be the dominant influence (Tubiello et al. 2007; Stokes et al. 2010; Cullen et al. 2012).

Temperature increases could benefit forage production in winter and early spring in the high rainfall temperate areas of the south-west, though this benefit is likely to be offset by a shorter growing season and more rapid soil water depletion in late spring (Stokes et al. 2010; Cullen et al. 2012; Henry et al. 2012). In warmer areas of WA, increased temperatures will increase heat stress and evaporative demand.

Increased CO₂ concentrations will improve the water use efficiency and growth of legumes more than forbs, which in turn will benefit more than grasses (Newton et al. 2014). Generally, increased temperatures will favour C₄ over C₃ species and increased CO₂ concentrations will increase plant water use efficiency more in C₃ species than C₄ (Harle et al. 2007; McKeon et al. 2009; Stokes et al. 2010; Bell et al. 2011; Henry et al. 2012). Consequently, climate change may alter species composition in native and improved forages (Harle et al. 2007; McKeon et al. 2009; Stokes et al. 2010; Bell et al. 2011; Henry et al. 2012). The greatest changes are most likely to occur where species are at their physiological limits (Southern Livestock Adaptation 2030 [SLA2030] 2012c).

Modelling of five perennial grass weeds currently present in WA suggests that a reduction in the extent of climatically suitable habitat will occur by 2050 (Gallagher et al. 2013). Suitable habitat for species in the southern half of WA will move further south, while species habitats in the north of the state are constrained closer to coastal areas. It should be noted that this study did not account for improved water use efficiency resulting from greater CO₂ concentrations.

The digestibility and protein content of forages is likely to decrease as temperatures and CO₂ concentrations increase, with C₃ plants affected more than C₄ plants (Rotter & van de Geijn 1999; Harle et al. 2007; Tubiello et al. 2007; Stokes et al. 2010; Henry et al. 2012). This decline in forage quality could be exacerbated if C₄ plants became more dominant (Harle et al. 2007; Stokes et al. 2010). However, a general decline in digestibility and protein content may be offset by increased growth rates of better quality species and the ability of grazing animals to preferentially select those species. A long-term, 'Free air carbon dioxide enrichment' experiment in temperate New Zealand found that legumes and forbs — non-grass herbaceous species — grew faster than grasses and were preferentially grazed. Consequently, legumes and forbs in the free air carbon dioxide enrichment pasture made up a larger part of the diet of grazing sheep compared to sheep grazing pasture under ambient atmospheric CO₂ concentrations (Newton et al. 2014).

Besides affecting animal growth and reproductive success, changing pasture or forage quality and quantity can also affect wool fibre diameter and introduce increased vegetable faults if weed species increase (Harle et al. 2007).

Greater rainfall intensity associated with tropical cyclones may also increase encroachment of woody plants into grasslands in pastoral areas. Increased tree recruitment positively correlates with the frequency of extreme rainfall events in Australia (Holmgren et al. 2013). Kulmatiski and Beard (2013) suggested that an increase in rainfall intensity would increase deep recharge of soil water, which favours deep-rooted, woody vegetation.

While there are uncertainties about future levels of greenhouse gas emissions and modelling of the consequences, most models project that forage production will progressively decline over the next 60 years. McKeon et al. (2009) estimated that forage production would remain largely unchanged or increase under a scenario where temperature, atmospheric CO₂ and rainfall all increase (Figure 4.9a). However, in the more likely event of rainfall declining by 10% — as is projected for the south-west of the state by 2030 — estimated forage production may decline by up to 10% across the agricultural areas and southern rangelands and by 10–20% across the rest of WA (Figure 4.9c).

Studies using an SRES A2 emission scenario and a different suite of global climate and forage production models showed that forage productivity would progressively decline over much of the agricultural area of WA (SLA2030 2012b; Moore & Ghahramani 2013). The percentage decline in livestock productivity and profitability will be greater than the decline in pasture growth because the rates of pasture utilisation fell as the total pasture production declined while the amount of ungrazed pasture required to protect the soil from erosion remained unchanged (Figure 4.10).

The effects were greatest in lower rainfall areas (Figure 4.11b) and varied between enterprise type, but were generally greatest for those growing wethers (Figure 4.11a).

The profitability of livestock enterprises is projected to remain relatively unchanged at high rainfall sites (Figure 4.11b). Eckard et al. (2008) found that the projected yield of a kikuyu and subclover pasture in Albany increased in 2030 and 2070 under all emission scenarios. Increases ranged between 14% and 29% in 2030 and between 9% and 29% in 2070. The model showed that under the high-emission scenario — CO₂ concentration of 550ppm, temperature increase of 3.3°C and 21% rainfall reduction — warming stimulated kikuyu to start growing earlier in spring and improved the early winter growth of subclover. However, it resulted in an earlier finish to the subclover growing season. Declining rainfall also shortened the spring growing season of kikuyu.

Most modelling suggests that the interannual variability in pasture production is likely to increase where rainfall declines (McKeon et al. 2009; Cullen et al. 2012). Historically, rainfall variability in pastoral areas has made it difficult to determine the appropriate livestock carrying capacity to maintain long-term forage and soil condition. Determining carrying capacity is likely to become more critical under changing climate conditions (McKeon et al. 2009). The combination of long-term rainfall decline over large areas of grazing land in southern WA and continued climate variability is likely to place severe stress on rangeland ecosystems, grazing enterprises and rural communities (McKeon et al. 2009).

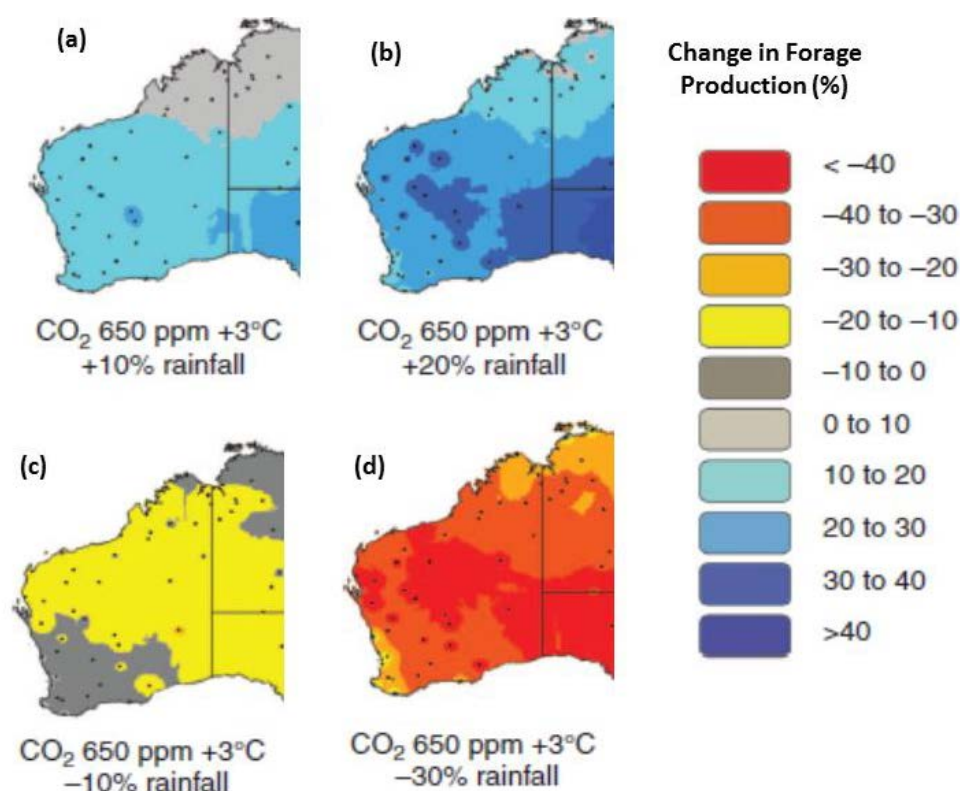


Figure 4.9 Projected changes in forage production for a high-emission scenario (CO₂ concentration of 650ppm and temperature increase of 3°C) with rainfall increasing by (a) 10%, and (b) 20%, and rainfall declining by (c) 10%, and (d) 30%. Dots indicate the sites where forage production was estimated (McKeon et al. 2009)

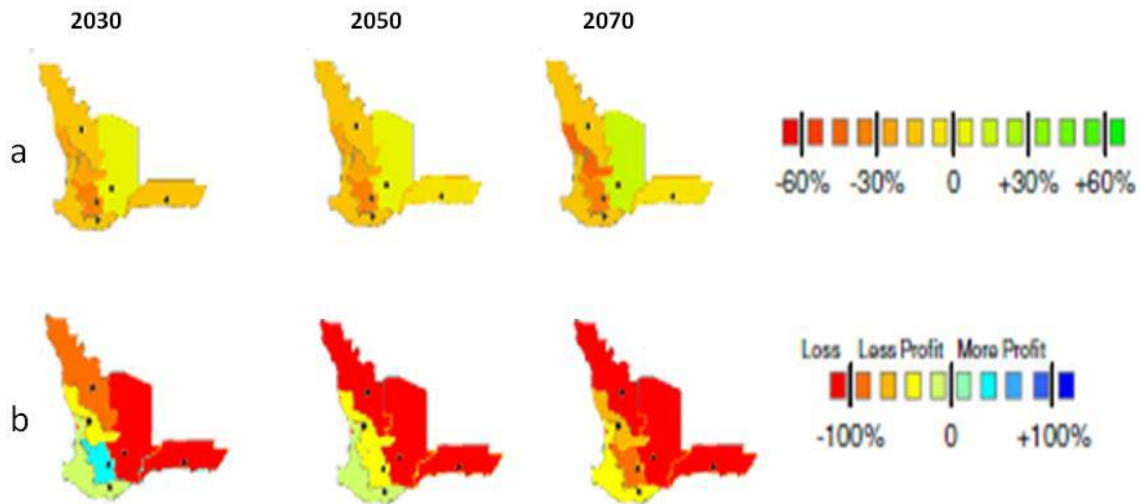


Figure 4.10 Modelled changes in (a) above-ground net primary productivity of pastures, and (b) long-term average operating profit from Merino ewe enterprises resulting from climate changes projected by four global climate models under the SRES A2 scenario. Values shown are changes relative to 1970–99 base scenario and are for optimal sustainable stocking rates (SLA2030 2012a)

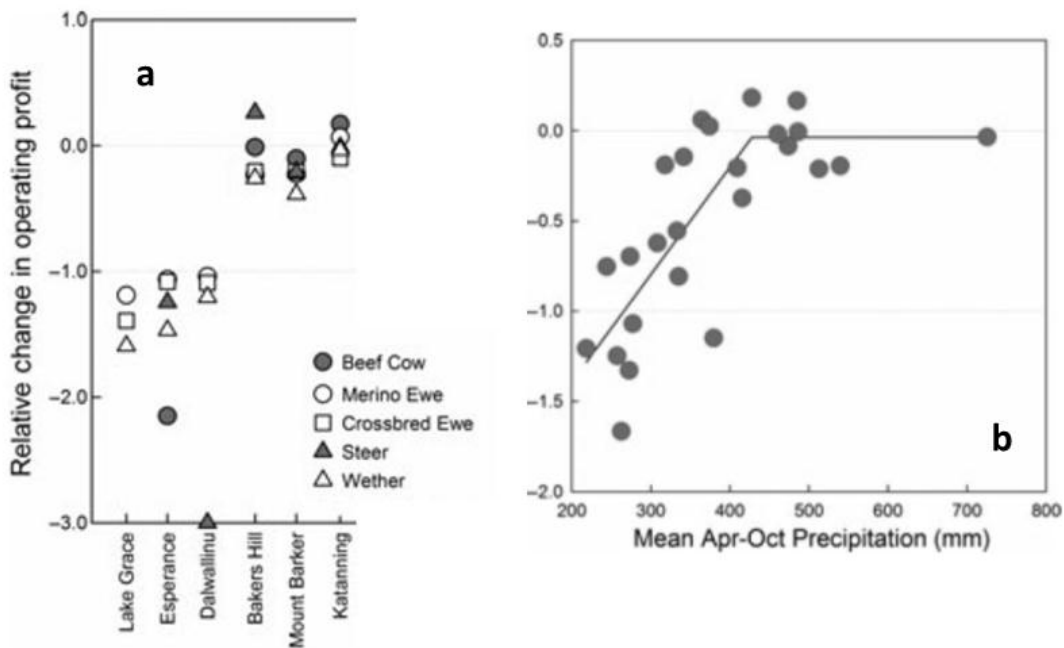


Figure 4.11 Change in operating profit under projected climate in 2050, (a) relative to historical climate for various livestock enterprises in WA, and (b) as a function of growing season rainfall at 25 sites across southern Australia. Values were determined at optimal sustainable stocking rate and with a SRES A2 emission scenario (Moore & Ghahramani 2013)

4.4.2 Animal husbandry

Heat stress

Climate warming may benefit livestock during cooler periods and in southern parts of WA by reducing feed requirements (lower energy maintenance costs) and increasing the survival rates of young animals or shorn sheep during cold and wet periods. However, during warm periods, particularly in the north of the state, higher temperatures will increase heat stress in livestock (Howden et al. 1999; Rotter & van de Geijn 1999; Black et al. 2008; McKeon et al. 2009).

Heat stress can limit the growth and reproductive success of sheep and cattle and reduce milk production in dairy cattle (Howden et al. 1999; Rotter & van de Geijn 1999; Harle et al. 2007; McKeon et al. 2009; Stokes et al. 2010; Henry et al. 2012). A warming climate may also increase the exposure and susceptibility of livestock to parasites and disease (Stokes et al. 2010).

A simple temperature–humidity index estimated using daily maximum temperature and dewpoint temperature can be used to indicate heat stress. When the daily index exceeds 80, cattle will stress. Howden and Turnpenny (1998) calculated that between 1959 and 1997, the number of days the temperature–humidity index exceeded 80 ranged from 70–80% in the far north of WA to 0–10% in the south. Under a warmer climate, the number of heat stress days increased by up to 30% in northern parts and by 10% in southern parts.

Stock water

Increased temperatures will increase livestock water requirements (Table 4.2). In south-east Queensland, a 2.7°C increase in air temperature is estimated to increase cattle water requirements by 13%, with further nonlinear increases at higher temperatures (Harle et al. 2007). However, if the temperature of stock water becomes too high — more than 27°C for cattle — water and feed intake may decrease, affecting animal productivity (Higgins & Agourdis 2008).

Table 4.2 Water requirements of cattle at various air temperatures (Higgins & Agourdis 2008)

Air temperature (°C)	Litres of water per kilogram of dry feed	Litres of water for a 500kg cow
5	0.55	30.7
16	0.79	38.2
27	1.07	51.5
32	1.51	73.4

Future changes in temperature and rainfall may also affect the quality of stock water. Water temperature influences the bioavailability of toxic elements and compounds. Warm water (15–30°C) can facilitate toxic blooms of cyanobacteria (Australian and New Zealand Environment and Conservation Council & Agriculture and Resource Management Council of Australia and New Zealand 2000a, 2000b). Declining rainfall and increased evaporation may increase the salinity of dams and waterways, and increased storm intensity may increase the amount of sediment and organic debris washed into sources of stock water.

4.5 Climate change and horticultural crops

Summary

- Climate projections suggest that:
 - chill accumulation could be reduced by up to 100 hours in the south-west, which could affect heat-sensitive crop species or varieties
 - increased maximum temperatures will reduce fruit quality and could cause burning of some leafy horticultural crops
 - the south-west region will remain ideally suited for producing high quality grapes and wine
 - banana production at Carnarvon is likely to be relatively unaffected by increased temperature at least until 2030, but production may be negatively affected at Kununurra
 - lettuce production may not be viable at Gingin by 2030 unless more heat-tolerant cultivars become available
- Farmers identify access to water as the single biggest concern in relation to future climate change.

Increased temperature and atmospheric CO₂ concentration, altered rainfall regimes and associated water availability, and increased risk of climate variability and storm intensity are all likely to affect horticulture in WA.

4.5.1 Current trends

Reid (2010) examined temperature and rainfall records for 23 WA locations that support horticultural production. Reid (2010) found that rainfall had declined at all locations over the last century and there had been a small increase in the number of days with temperatures above 35°C or 38°C; however, in many cases the number of chilling hours had increased.

In the Margaret River region, growing season minimum temperature dropped significantly (−0.34°C per decade) over the period 1977–2009, while maximum temperature rose significantly (0.29°C per decade) resulting in no significant change in the growing season average temperature (Webb et al. 2012). These temperature changes are attributed to proximity to the coast moderating the climate of the region (Ward 2009). Consequently, ripening times of Cabernet Sauvignon grapes did not change significantly at Margaret River between 1977 and 2009. In contrast, Victoria and South Australia have seen significant trends to earlier ripening (Webb et al. 2012). Webb et al. (2012) also found there was a significant negative correlation between time to ripening and growing season average temperature and a significant positive correlation between modelled soil water content at 0.7–1.0m depth and time to ripening.

Two studies of pome fruit have shown that changes in pome fruit bloom phenology may be occurring more slowly in the southern hemisphere than the northern hemisphere (Darbyshire et al. 2013a).

While Morgan et al. (2008) reported that producers had observed increased incidence of frosts and cool mornings, Reid (2010) found that frost incidence has contracted over the last 20 years. Reid did not attempt to link these climatic changes to horticultural productivity over the period.

A survey of 12 grape growing businesses in the Margaret River region in 2009–10 found that none of the participants considered production to have been negatively affected by climate change (Galbreath 2014). While rainfall in the south-west region declined by 15% between 1976 and 2008 (Ward 2009), respondents attributed the adoption of water-saving adaptations, such as increasing plant available soil water, reusing waste water and improved irrigation methods, as economic imperatives rather than as climate adaptation per se (Galbreath 2014).

Reid (2010) and Morgan et al. (2008) report that water supply is the issue of greatest concern to producers.

4.5.2 Future projections

Higher minimum temperatures will affect tree crops, such as cherries and nuts, because chill accumulation could be reduced by up to 100 hours. Without a change to more heat-tolerant species or varieties, some tree crops in the south-west are likely to experience poor fruit set and variable bud burst (Carmody 2010b). Increased maximum temperatures will affect fruit quality and could cause burning of some leafy horticultural crops. Increased temperatures are also likely to lead to greater prevalence of some fungal and bacterial diseases, particularly insect-borne diseases, though decreased humidity could reduce the incidence of some aerially dispersed fungal diseases (Carmody 2010b).

A study of grape growing in the Margaret River, Pemberton and Mount Barker areas found proximity to the coast has a highly moderating effect on climate with several microclimates identified within the areas (Ward 2009). The study found higher temperatures would reduce winter chilling and result in phenological changes such as early or delayed budburst, earlier harvest, compressed growing season and ripening changes, such as promoting sugar ahead of aroma and flavour development. Lower rainfall in winter and spring would reduce run-off for water supply, reduce the risk of rain occurring during harvest of late varieties and promote more effective disease control. The study concluded that climate change would change varietal characters and wine styles, but

...wine regions in south west Western Australia will remain ideally suited to further viticulture development for the production of high quality grapes and wine in the future (Ward 2009, p. 40).

Shortening the season can bring harvest forward into the warmer part of the season, and present logistical problems, such as intake scheduling, and truck and harvest equipment availability (Webb et al. 2010).

Banana production at Carnarvon is likely to be relatively unaffected by increased temperature at least until 2030 but it may be affected at Kununurra (Deuter et al. 2012a). When the critical temperature for bananas (38°C) is exceeded, exposed fruit

can be sunburnt by bright sunshine. Under an A1F1 emission scenario, monthly average temperatures at Carnarvon in 2030 are expected to remain below the critical temperature despite increasing by 1.2–3.1°C. While temperature changes in Kununurra (0.3–0.5°C) are likely to be less than at Carnarvon, the changes will be enough to increase the amount of time that the critical temperature is exceeded from the current time period of one month (November) to three months (October to December).

Rogers (2013) found that increased temperatures at Manjimup would alter development and harvest times of vegetable crops, allow alternative crops such as capsicum to be grown, extend the growing season of some varieties and preclude the growing of others (Table 4.3). A 4°C temperature increase or an increase in the number of days over 35°C would reduce quality and yield.

The amount of time that the critical temperature threshold for lettuce (28°C) is exceeded could increase by two weeks at Gingin by 2030 under the A1F1 scenario (Deuter et al. 2012b). Increasing temperatures will decrease lettuce quality and could stop summer production. If more heat-tolerant lettuce cultivars are available up to and after 2030, this impact will be ameliorated (Deuter et al. 2012b).

An assessment of the impact of 1°C, 2°C and 3°C temperature increases on pome fruit production found that three WA sites were more adversely affected than others in Australia, and there was the potential to affect future production (Darbyshire et al. 2013b). Darbyshire et al. (2013a, 2013b, 2013c) found there were differences among model outputs and stated that the models they tested would require further investigation to avoid mismanagement or maladaptation.

Decreased annual rainfall will almost certainly continue to decrease run-off and groundwater recharge and increase variability in dam storage volumes in the southern half of WA (see Chapter 2.4.7). Morgan et al. (2008) identified access to water as the single biggest concern producers had in relation to future climate change, with producers expressing concern about ongoing capacity to grow crops and provide water for livestock.

In addition to reduced streamflow and groundwater recharge, water demand in the south-west is projected to increase by about 35% by 2030 (Bennett and Gardner 2014). The greatest growth in demand for water is expected in the Perth and Peel regions, growing from 631GL in 2008 to 912GL in 2030 (assuming there is no increase because of climate change; Thomas 2008). Regions most likely to be affected by climate change include Greenough, Moore, Perth, Peel and Preston, where climate change could result in a compound increase in demand of 1% per year, totalling 120GL per year by 2030 (Thomas 2008).

Table 4.3 Effect of increased temperatures on horticultural production at Manjimup (Rogers 2013)

Crop	Current conditions	1°C increase	2°C increase	3°C increase	4°C increase	5 days over 35°C
Lettuce	Harvested from December to May	2–3 days quicker to harvest	Change to summer-type varieties, increased tip burn	May require protective shading during summer, transition period becomes longer	Avoid growing lettuce in summer. Harvesting during winter possible	Decline in quality and yield
Baby leaf lettuce, spinach, rocket	Harvested from October to June	2–3 days quicker to harvest	3–5 days quicker to harvest, change varieties, extended harvest period	6–7 days quicker to harvest, new varieties, all year round production	8–9 days quicker to harvest, new varieties, year round production	Germination problems in summer if >35°C, fringe burn reduces leaf quality
Capsicum	Not suitable area for production	Harvesting possible from January to March	Harvesting possible from January to April	Harvesting possible from mid-December to May	Harvesting possible from December to late May	Sunscald and blossom end rot
Broccoli and cauliflower	Harvested all year round	Earlier maturity	Use varieties adapted to warmer conditions	Less cool-season varieties in schedule	Increased 'buttoning', premature heading, tip burn, hollow stem and white blister, harvest window reduced to June to October	Quality decreases

The Preston region could enter significant water supply deficit by 2025 because the region is highly dependent on irrigated pasture production. Demand for irrigation water may increase in a warmer climate and supply is likely to decline because of reduced streamflow into dams (Thomas 2008). Climate change impacts on water demand should be less marked further south in the Vasse, Blackwood, King and Esperance regions, and climate change is unlikely to have a major impact on water demand or supply in the Kimberley (Thomas 2008).

Those regions where water demand is most likely to increase under a changing climate are also the regions where demographic and economic growth is greatest, and a hotter, drier climate is most likely to depress surface water and groundwater yields. In these areas, agricultural and other rural water demands are likely to be constrained by water availability, competition from growing urban water demands and climate impacts.

4.6 Impact on weeds, pests and diseases

Summary

- Climate change and subsequent changes to agricultural enterprises and practises will alter the distribution and activity of weeds, pests and diseases.
- This could have positive and negative effects:
 - Increasing humidity and summer rainfall will improve conditions for blowfly strike on sheep, the vectors of bluetongue virus, soil-borne diseases such as *Phytophthora cinnamomi*, and fruit diseases such as *Anthraco*se in avocados.
 - Declining summer rainfall and soil moisture will reduce the risk of pathogens such as liver fluke and stripe rust.
- In general, there will be a southwards and westwards movement of adaptive area.
- Wet tropics weed species may make the greatest move — over 1000km.

4.6.1 Weeds

Change in adaptive area

CSIRO studies modelled how climate change in 2030 and 2070 might alter the distribution of 41 weed species (sleeper species) that currently pose a threat to Australian agriculture (Scott et al. 2008; Scott 2009). The studies found that most of these sleeper weeds would shift south, with wet tropics species making the greatest move of over 1000km. The south-west is one of two Australian regions most at threat from sleeper weeds under the current climate and with climate change.

Michael et al. (2011) identified 20 weed species posing the biggest threat to the Northern Agricultural Region and then considered how climate change would alter their impact on agriculture. The five species likely to experience the greatest increase in severity of impact were matricaria (*Oncosiphon piluliferum*), windmill grass (*Chloris*

truncata), Calomba daisy (*Oncosiphon suffruticosum*), Bathurst burr (*Xanthium spinosum*) and onion weed (*Asphodelus fistulosus*).

With the increase in summer rainfall there may be an increase in the prevalence of summer weeds that use water and nutrients that could otherwise be used by crops sown in autumn (van Rees et al. 2011).

Tolerance to herbicides

Ziska and Teasdale (2000) observed an increased tolerance to glyphosate in the perennial weed quackgrass at elevated levels of CO₂ concentration. However, Downey et al. (2012) found no clear trend among 24 weed species, with some species showing higher tolerances and others showing no difference when grown under elevated CO₂ concentration. More work is needed in this area because increased tolerance to herbicides would significantly affect weed management options in the future.

4.6.2 Pests and diseases of livestock

It is likely that disease risk will alter as livestock density, distribution, production and trade respond to climate change (Black et al. 2008). Animal pests and diseases are linked spatially and temporally to weather and climate (Stokes et al. 2010). Consequently, climate change may promote disease and pest outbreaks moving from low latitudes to middle latitudes (Tubiello et al. 2007), increase the rate of development of certain pathogens or affect the numbers of competitors, pathogens or parasites of disease vectors (Black et al. 2008). For example, the range of the cattle tick (*Rhipicephalus microplus*) and *Culicoides* vectors of bluetongue virus are likely to extend southwards in areas where summer rainfall increases (Black et al. 2008; Stokes et al. 2010). Blowfly strike on sheep may also increase where humidity and summer rainfall increase.

Climate change will not increase the risk from all diseases. Diseases that are transmitted primarily by close contact between hosts or that are food-borne (such as mastitis, salmonellosis and infectious bronchitis) will be little affected (Black et al. 2008). In some cases, the risk from pests and disease may decline. For example, the snail intermediate hosts of the liver fluke (*Fasciola hepatica*) depend on moisture to survive and multiply, so areas where rainfall and soil moisture decline, particularly in summer, may be at less risk of becoming infected (Black et al. 2008). Likewise, the area suitable for temperate species, such as lice, may contract (Henry et al. 2012).

4.6.3 Pests and diseases of horticultural and broadacre crops

Disease activity is greatest during spring in southern WA (Anderson & Garlinge 2000). This period is most suited to fungal diseases that grow best in warm and humid conditions. Most fungal spores germinate when leaves are moist. Some spores, such as those of *Septoria* diseases, require rain splash to spread to new leaves and some, such as those of powdery mildew, require only high humidity for infection.

Cereal crop production has evolved around the characteristically dry summer conditions that are typical of southern WA. This period is critical to break the disease cycle of cereal rust diseases. Rust diseases rely on living host plants and do not

have a resting stage. Host plants normally cannot survive dry summer conditions and hence rust carryover is very low after a dry summer. Unusually wet summer conditions can greatly increase risk of wheat rusts (Anderson & Garlinge 2000).

Soil moisture affects root diseases:

- directly through conditions for infection and also indirectly through the capacity of the plant to tolerate root disease
- by affecting the rate of breakdown of infected trash
- by directly influencing the type and amount of root disease.

When the root system is damaged by disease, plants are less able to take up water and nutrients or tolerate stresses such as waterlogging and drought. Early in the season, very wet to waterlogged conditions can favour soil organisms such as *Pythium*. Without waterlogging, *Pythium* spores are less able to move to developing roots and fungi that cause take-all and crown rot, and are better able to infect and colonise plants. Root diseases can often become more evident and induce greater effects on production under drier than normal crop finishing conditions (Anderson & Garlinge 2000).

The impact of climate change is not likely to be uniform across all plant pathogens and hosts in all locations, so generalisation is difficult (Garrett et al. 2006; Luck et al. 2011). Climate change could alter stages and rates of development of the pathogen, modify host resistance, and result in changes in the physiology of host–pathogen interactions (Garrett et al. 2006). Changes in plant architecture may also affect the microclimate in the crop canopy and thus risks of infection.

The way that abiotic — chemical and physical characteristics of the environment — stress factors interact will determine how climate change will affect host plants and pathogens. Abiotic stress, such as heat and drought, may contribute to plant susceptibility to pathogens or it may induce general defence pathways that increase resistance (Garrett et al. 2006). The life cycle of some pathogens, such as stripe rust (*Puccinia striiformis* subsp. *tritici*), will be limited by a reduction in rainfall and an increase in temperature. Other climatic factors, such as increasing atmospheric CO₂, may provide more-favourable conditions for pathogens such as crown rot (*Fusarium pseudograminearum*).

The effect of climate change on alternative hosts may also affect disease prevalence. An increase in summer rainfall may enable host plants to survive over summer creating a 'green bridge' for pathogens to survive until crops are established in autumn. The green bridge has traditionally been of concern for the survival of rust species in WA. Increased summer rainfall can also increase humidity and soil saturation during warm periods, thus increasing the severity and incidence of soil-borne diseases, such as *Phytophthora cinnamomi*, or fruit diseases such as *Anthraco*se in avocados (Reid 2010).

Climate change may also alter the stages and rates of development of a wide range of insect pests and so alter the timing and severity of pest outbreaks (Web & Whetton 2010). Many pests are restricted geographically and seasonally by climate suitability,

so climate change may lengthen the season when certain pests are active and expand their geographical range (Reid 2010). For example, higher winter temperatures and more summer rainfall can increase humidity during warm periods which increases the risk of insect pests, such as fruit spotting bug and *Monolepta* species in avocados, or fruit fly in citrus (Reid 2010). These same changes can also affect the distribution, activity and effectiveness of natural predators of agricultural pests (Thomson et al. 2010).

4.7 Impact on resource condition

Summary

- Where drier, warmer and more variable conditions reduce plant cover:
 - wind erosion risk will increase
 - increased rainfall intensity from tropical cyclones and storms will further increase the risk of water erosion
 - soil organic carbon could be expected to decline.
- Livestock stocking rates will require careful management to maintain sufficient groundcover to avoid increasing the risk of soil erosion.
- Secondary salinisation could be expected to decrease as rainfall decreases, but this decrease may be offset by less plant transpiration and more intense storms causing episodic recharge.

Natural resource condition has three primary drivers: climate, land characteristics and land management. The current condition of natural resources on farms in the south-west of WA is mixed. There has been progress in areas such as managing wind and water erosion, but the status and trend for many other indicators of resource condition is 'adverse' (Schoknecht et al. 2013).

In general, the impact of future climate change on natural resource condition is poorly understood given the uncertainties in climate trajectories and the complex interactions among climate, land characteristics and land management. However, it is possible to identify some broad risks and trends.

Declining rainfall over southern WA associated with increased drought and increased rainfall intensity from tropical cyclones and storms will increase the risk of wind and water erosion, particularly if drier, more variable conditions reduce plant cover (Harle et al. 2007; Stokes et al. 2010).

In the south-west of WA, the last decade has seen a trend of fewer erosive rainfall events at the break of the season and more potentially erosive summer storms in the eastern wheatbelt and south-eastern coastal areas (Schoknecht et al. 2013). Most erosion events over the past 15 years have been associated with intense summer storms across the south-west and decaying tropical cyclones in the eastern wheatbelt and adjoining rangeland catchment areas (Schoknecht et al. 2013). Summer storms may worsen in the future because tropical cyclone intensity is projected to with tropical cyclones tracking further south.

Where climate change reduces plant growth, soil organic carbon could be expected to decline (Baldock et al. 2012; Schoknecht et al. 2013). Modelling suggests that declining rainfall under future climates will reduce pasture growth and increase the length of dry periods between growing seasons. Consequently, livestock stocking rates will require careful management to maintain sufficient groundcover to avoid increasing the risk of soil erosion (Moore & Ghahramani 2013).

Changing rainfall amount, distribution and intensity and associated vegetation cover and water use have the potential to cause substantial changes in landscape hydrology and salinity risk, though these processes have yet to be fully evaluated (Harle et al. 2007; McKeon et al. 2009; Stokes et al. 2010). While rates of secondary salinisation could be expected to decrease as rainfall decreases, this decrease may be partially offset if more-intense storms cause episodic recharge events (van Ittersum et al. 2003; John et al. 2005; Ludwig et al. 2009; Howden et al. 2013). Rogers (2013) identified the Perth, Manjimup and Pemberton horticultural areas as among Australia's horticultural areas most at risk of increasing salinity in the future as declining rainfall reduces run-off into dam and recharge of aquifers used for irrigation water sources.

It has been suggested that the area planted to perennial vegetation, such as oil mallees and saltland pastures, may increase in marginal areas where cropping becomes less profitable. Increased planting of perennial vegetation could act to further ameliorate salinisation in future (John et al. 2005). However, in marginal areas, producers' ability to make these changes may decline if climate change decreases financial returns from conventional agriculture (John et al. 2005).

If heat stress increases in the future, it is likely to increase livestock water requirements and may exacerbate overgrazing near watering points in pastoral areas (Howden et al. 1999; Harle et al. 2007).

5 Adapting to climate change

Summary

- The effects of climate change will vary regionally and by enterprise, but all agricultural industries will need to deal with some level of climate change in the coming decades.
- There are three broad levels of adaptation that have increasing benefit but also increasing complexity, costs and risk:
 - incremental adaptations, such as adjusting practices and technologies
 - transitional adaptations, such as changing production systems
 - transformative adaptations, such as relocating production.
- Enterprises in currently marginal areas are most at risk from climate change — southern rangelands and northern and eastern wheatbelt areas are most at risk.
- Incremental changes are likely to continue in the medium term (2020–30) across most sectors and regions, but transitional and transformative adaptations should also be considered in any longer-term planning and in marginal areas.

The ability to adapt to climate change depends on the ability to use existing resources in new ways to build productivity and profitability without depleting the natural resource base (Marshall et al. 2013). While the future trajectory of global greenhouse gas emissions is uncertain and the effects of climate change will vary regionally and by enterprise, all agricultural industries will need to deal with some level of climate change in the coming decades. As well as dealing with direct ecophysical impacts, producers will need to also deal with socioeconomic impacts.

At an international level, reduced agricultural productivity because of climate change and expanding global population is likely to increase prices, encourage more intensive management practices, trigger shifts in production areas and a probable global expansion in agricultural area, cause reallocation through international trade and reduce consumption (Nelson et al. 2014). At a local level, these changes are likely to affect the livability of regional communities, the occupational health aspects of working in hotter environments, labour availability, the cost and availability of insurance and cost of agricultural inputs such as water, power, fuel and chemicals.

Howden et al. (2010a) identified three levels of adaptation that producers and rural communities can take:

- adjusting practices and technologies (incremental)
- changing production systems (transitional)
- relocating production (transformative).

The benefits derived from each of these levels of adaptation increases as the degree of climate change increases; but so does the complexity, cost and risk associated with the change (Figure 5.1; Howden et al. 2010a).

Broadacre producers in WA have been adopting incremental (and to a lesser degree transitional) changes to deal with the consequences of a drying climate and declining terms of trade, but producers' ability to adapt in the long term is constrained by their adaptive capacity. The need for transformational adaptation is driven by the potential for large or rapid changes in the suite of direct and indirect consequences of future climate that are beyond the adaptive capacity of incremental change (Rickards & Howden 2012). However, while incremental changes are now part of 'business as usual', transformational changes are comparatively poorly understood and potentially carry much greater social, economic and environmental risks (Rickards & Howden 2012).

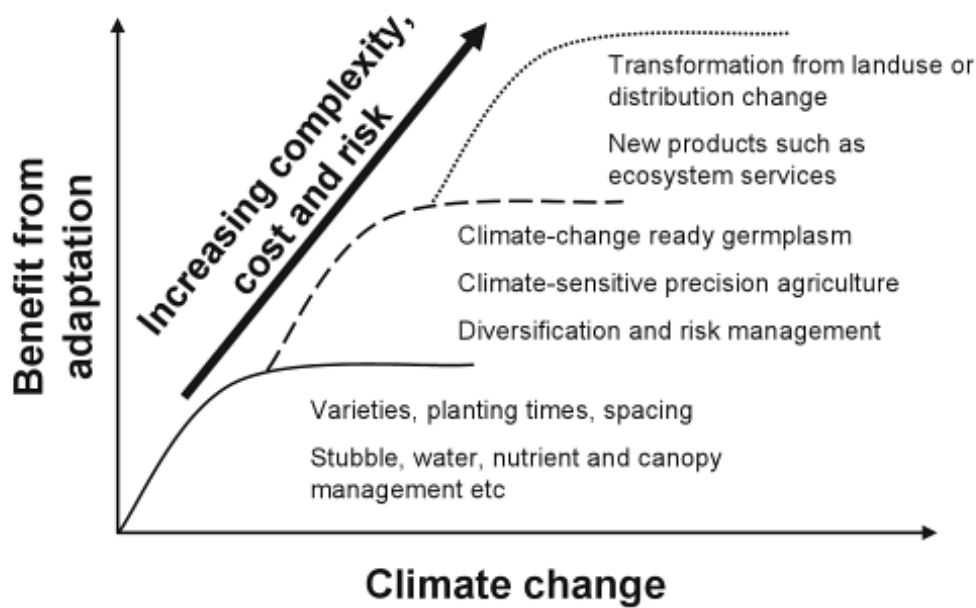


Figure 5.1 Conceptual relationship between the levels of adaptation required as the degree of climate change increases and the associated risk, cost and complexity (Howden et al. 2010a)

This section explores some of the adaptation options that have been suggested for WA's agricultural sectors to deal with the impacts of climate change. For a more comprehensive review of these topics in the broader Australian context, refer to Rickards (2013) review of the literature published between 2009 and 2012.

5.1 Broadacre mixed farming

Summary

Adaptation to historical climate change:

- Technological and management improvements doubled WA wheat yields over the last 30 years.
- There have been large productivity gains in the cropping industry compared to the livestock industry.
- There has been a general reduction in the rate of productivity growth across Australia's broadacre farms since the late 1990s.

Adaptation to future climate change:

- Many of the incremental technological and management adaptations suggested for cropping are currently considered 'best practice', and there is scope for increasing the level of adoption of these.
- It is prudent for most farmers to continue making incremental adaptations and to wait before making transformational changes.
- Wheat will continue to be the principal broadacre crop grown in WA.
- The future of livestock farming is less certain than cropping:
 - Combinations of adaptations could improve or maintain livestock enterprise profitability to 2030.
 - By 2050–70 a complete change of the feed base may be required in lower rainfall areas unless there are sustained improvements to terms of trade.
- The north-eastern agricultural region is particularly vulnerable to the impacts of climate change:
 - Current crop-dominant mixed farming systems could become economically unviable in 20 years.
 - Systems combining trade cattle, carbon farming and opportunistic cropping may improve viability by reducing risk in low rainfall years.
 - Farmers may be willing to permanently revegetate consistently unproductive soils if they receive financial support.
- Terms of trade are critical in determining the future economic impacts of climate change and consequent adaptation strategies:
 - If global grain yields decline, grain prices and agricultural commodities in general are likely to rise.
 - Higher prices may facilitate continued farming in marginal areas.
- The financial circumstances of farmers influences their adoption of practices requiring large up-front investments:
 - New financial arrangements could be used to facilitate capital purchases and short-term farm inputs.
 - Various types of insurance could help manage climate risk.

5.1.1 Current trends

As discussed in Chapter 4, climate change has had relatively little impact on crop yields in WA to date (Ludwig et al. 2009; Asseng & Pannell 2013). Rather, it has been declining terms of trade, technological advances and ongoing climate variability that have mostly driven the changes in WA farming systems (Morgan et al. 2008; Asseng & Pannell 2013; Fisher et al. 2014). Technological and management changes, such as new crop varieties, increased fertiliser use, reduced tillage, stubble retention, early sowing, better weed control and break crops, have doubled WA wheat yields over the last 30 years (Morgan et al. 2008; Asseng & Pannell 2013). The slowing in the rate of increase in wheat yield per hectare evident after the late 1990s has been attributed to producers reducing inputs (risk) in response to more variable climate conditions (Norwood 2015).

Kingwell et al. (2013) examined the financial performance of 249 wheatbelt farms between 2002 and 2011 and found that average farm productivity and profitability improved, while producers' underlying terms of trade remained the same. Sixty-four per cent of farms were classed as 'growing' or 'strong'. Making better use of existing technologies, taking advantage of efficiencies of scale and shifting to greater dependence on cropping, especially wheat production, were identified as successful adaptation strategies. Thirty-eight per cent of crop and mixed enterprise farms were classed as 'growing' compared to only 23% of livestock farms (Figure 5.2). Total factor productivity for crop farms was triple that of livestock farms, and crop farms showed increasing profitability while livestock farms showed no growth in profitability (Kingwell et al. 2013).

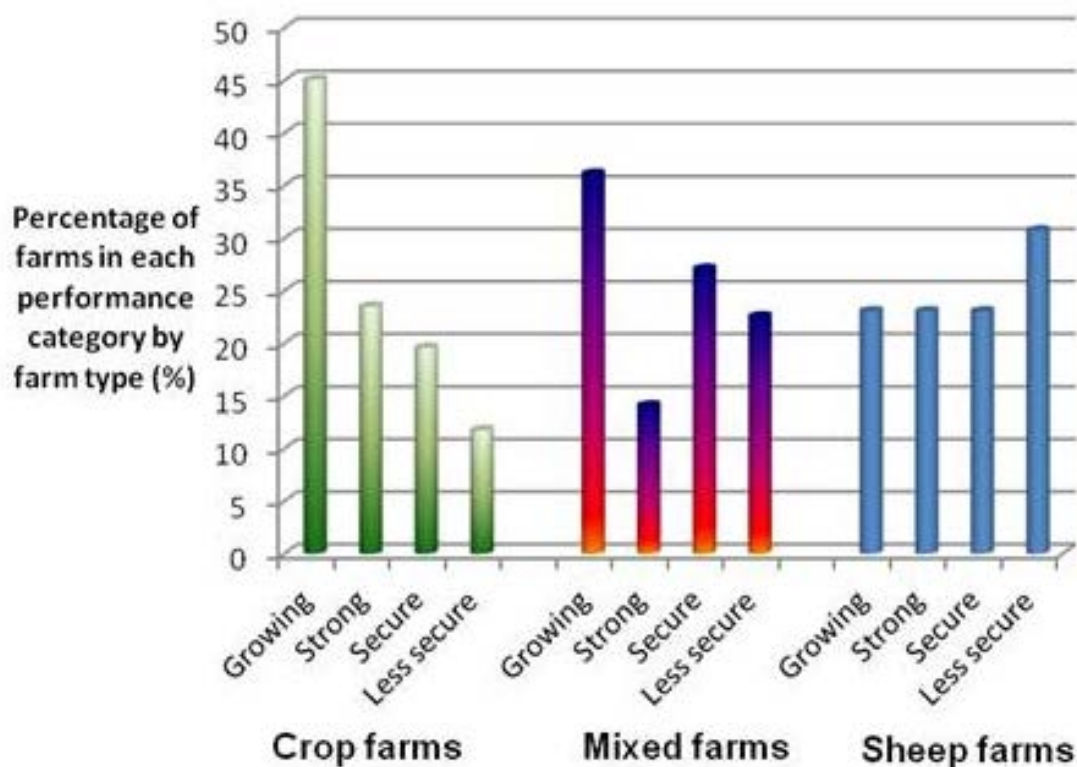


Figure 5.2 Percentage of farms in each performance category by farm type (Kingwell et al. 2013)

This result is representative of broadacre farms across Australia (Figure 5.3). Technological advances in the cropping industry during the 1980s and 1990s resulted in relatively large productivity gains relative to those seen in the livestock industry. This difference may reflect longer production cycles in livestock farming and hence slower transition to better technologies and production methods (ABARE 2010). The millennium drought and a long-term slowing of growth in public investment in agricultural research and development have been identified as major influences in a general reduction of productivity growth across Australia's broadacre farms since the late 1990s (ABARE 2010).

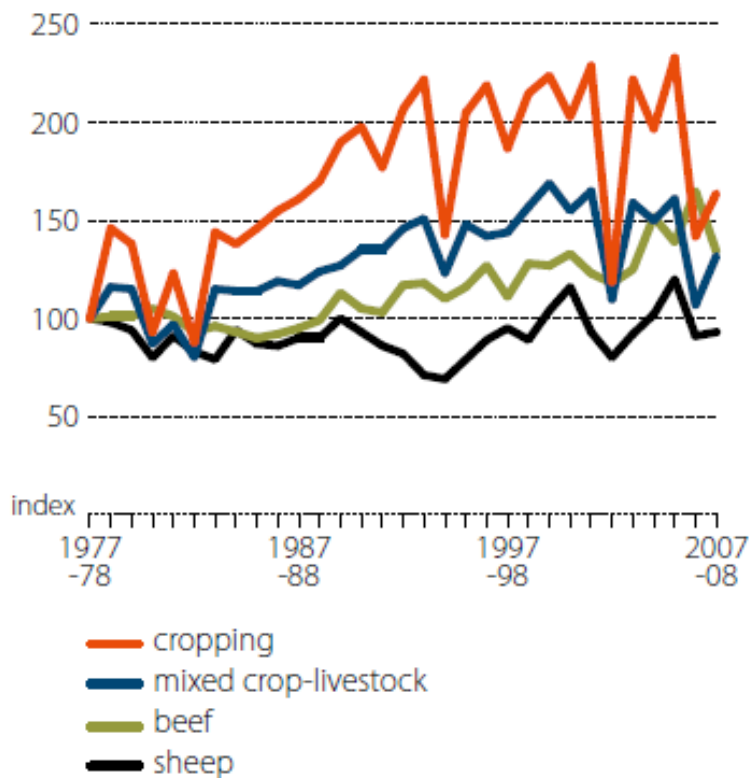


Figure 5.3 Changes in Australian broadacre farm total factor productivity since 1977 (ABARE 2010)

The central wheatbelt — regions M2, M3, M4 and M5 in Figure 5.4 — had the highest proportions of less secure farms (Kingwell et al. 2013). These regions fall within the area of highest frost risk (Figure 2.11) and have experienced declining rainfall (Figure 2.8). Consequently, crop yields in these areas were adversely affected by drought and frost in some years during the study period. In contrast, the northern agricultural regions (L1 and M1) and southern near-coastal region (M5) had the highest proportion of growing or strong farms; these regions have less risk of frost and some areas have seen an increase in spring rainfall.

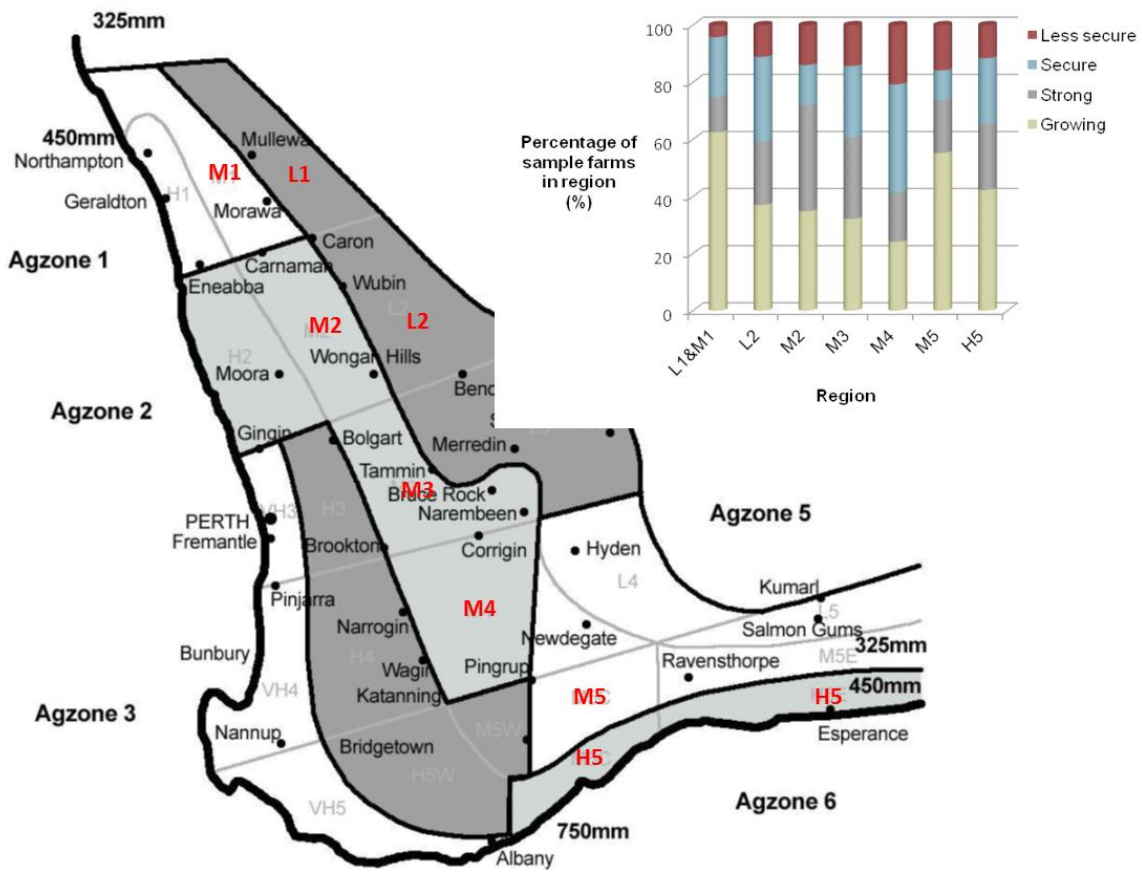


Figure 5.4 WA agricultural regions and percentage of farms in each performance category by region (Kingwell et al. 2013)

Plunkett's (2015) case study describing a farming enterprise at Tammin (on the boundary of regions M3 and L3 in Figure 5.4) provides a detailed description of how a farm that would be classified by Kingwell et al. (2013) as 'growing' is successfully dealing with declining terms of trade in an area where rainfall has declined (Figure 2.14) and climate variability, frost and heat stress risk are increasing. The central philosophy behind the business' success has been the move from maximising yields to maximising margins through efficiency of inputs and a focus on profits relative to risk. To this end, the producer has achieved economies of scale by increasing the farm size from 2800ha to 11 000ha and moving from mixed livestock and cropping to concentrate solely on cropping. Inputs have been reduced by moving to tramline farming and using variable application rates based on soil and crop testing, yield mapping and weedseeker technology. Plant available soil water has increased by moving to tramline farming, ameliorating soil constraints and introducing a ley year — a year when crops are not grown — for weed control and soil water recharge. Cropping rotations and agronomy are managed according to seasonal conditions. In addition, the producer has generated off-farm income from an aerial spraying business, and by storing and blending harvested grain on-farm, the producer has been able to achieve supply chain efficiencies and take advantage of favourable markets when selling grain.

The practices described above are among a suite of technology and management practices that are currently available to wheatbelt producers (Appendix C) and the

adoption and use of these methods needs to be considered “with respect to their impact on the farm system’s profitability over time adjusted for the amount of risk associated with those decisions” (Plunkett 2015, p. 1). Risk management and particularly conservative application of inputs appear to be widely used strategies that are exerting a moderating effect on yield and water use efficiency increases in the WA wheatbelt (Figure 4.6; Norwood 2015).

5.1.2 Future projections

Changes in crop and livestock production associated with future climate will vary with location, soil type and management. Crop and pasture yields are likely to increase in high rainfall south-western areas and generally decline in medium and low rainfall areas with the greatest declines on heavier, clay soil types. It is likely that the interannual variability will increase across most of WA. These changes will affect profitability and financial risk associated with farming enterprises, particularly at the margins of the wheatbelt.

Most of the climate change adaptations suggested for broadacre cropping in WA have been developed in response to historic changes in terms of trade and climate. Consequently, they are incremental and aimed at improving crop water use efficiency (increasing plant available soil water and its utilisation and crop breeding), optimising inputs (precision agriculture and variable rate technology) and managing according to seasonal conditions (using decision support tools) (Morgan et al. 2008; Moeller et al. 2009; Keating et al. 2010; Howden et al. 2010b; Ludwig & Asseng 2010; Oliver et al. 2010; Asseng et al. 2012a and 2012b; Asseng & Pannell 2013; Plunkett 2015). These practices are described in more detail in appendices B and C. There is some evidence that managing climate risk by being conservative in the use of agricultural inputs is constraining improvements in wheat yield and water use, and by extension, other crops (Figure 4.5 and Figure 4.6). It is not clear how future changes in climate will affect risk management and if reduced use of inputs will constrain, or even reduce, crop yield potential in marginal areas.

Asseng and Pannell (2013) suggested there is comparatively little scope for broadacre croppers to adapt to climate change in the short term because they have already adopted many of the incremental technology and management techniques currently considered ‘best practice’ (Appendix C). Kingwell et al. (2013) and Norwood (2015) agree that WA producers have been adopting best practices, but they add that producers in most parts of the south-west are likely to be able to continue adapting to projected climate change, provided that terms of trade do not become unduly adverse, they manage farm debt and have ongoing access to farm management and business education, improved crop varieties (especially wheat) and technologies. Adoption of best practices varies across the wheatbelt and there is considerable scope for improving the rate and extent of adoption (D Hall, pers. comm., 1 October 2015).

It should be noted that what is regarded as best practice varies in applicability across the wheatbelt and a thorough understanding of location-specific costs and benefits is needed before changes are undertaken. For example, claying to overcome non-wetting is preferred over the application of soil wetters in more productive, high

rainfall areas where costs can be quickly recouped. In low rainfall areas, soil wetters are preferred because they are cheaper (less financial risk) and they can be used with furrow or row sowing to concentrate water around sown seed to better facilitate germination and recharge deeper into the soil profile than would be possible with clayed soil (D Hall, pers. comm., 1 October 2015).

The financial circumstances of producers will continue to influence the adoption of those practices requiring large upfront investments such as updating machinery or applying soil ameliorants. This is of particular concern for those in marginal areas of the eastern wheatbelt who will come under the greatest pressure to adapt to climate change but are already suffering financially from a series of poor seasons.

Kirkegaard et al. (2011) point to “capital costs and depreciation of equipment, exposure to risky grain commodity prices and prolonged drought, and vigilance regarding the development of herbicide resistant weeds” as barriers to adopting the incremental changes offered by moving to conservation agriculture, precision agriculture and controlled traffic farming systems. Mugeru and Nyambane (2014) suggested that the technical efficiency of WA broadacre farms could be improved by using short-term debt, such as concessional loans and deferring taxes, to purchase farm inputs and maintain operations.

Wheat is perhaps the most resilient of WA’s broadacre crops (Hertzler et al. 2013) and is likely to continue to be the principal broadacre crop grown. Chapman et al. (2012) highlight the importance of crop breeding in climate change adaptation, particularly resistance to new and emerging pests and diseases and adaptation to higher temperatures and CO₂ concentrations. Internationally, it is projected that appropriate adaptations can maintain temperate wheat yields despite climate change (Challinor et al. 2014). Locally, Kingwell et al. (2013, p. 4) stated that the “forecast biologically robust performance of wheat” should help underpin the future profitability of crop production in WA. Hertzler et al. (2013) used the Real Options for Adaptive Decisions (ROADs) framework to assess whether producers in wheat-dominant agriculture will continue to adjust practices and technologies, change production systems or transform their industry. They found that wheat will continue to dominate agriculture in all of the rainfall zones, and concluded that:

The probability of switching out of wheat into sheep is low everywhere. For those producers already in sheep, the probability of exiting production and no longer farming is almost nil. In summary, as the climate changes and Western Australia becomes hotter and drier, the southern agroecological zones will more resemble the northern zones as they exist now. Wheat production may become less profitable and more risky, but it will remain the dominant form of agriculture in Western Australia (Hertzler et al. 2013, p. 76).

The long-term future of livestock producers is less certain compared to croppers in the wheatbelt, particularly in the low rainfall areas. In the short term, adaptation strategies combining technological, behavioural, managerial and policy options will be needed to offset the increasingly negative effects of climate change and may actually improve enterprise profitability (Figure 5.5; Thornton et al. 2011; SLA2030 2012b).

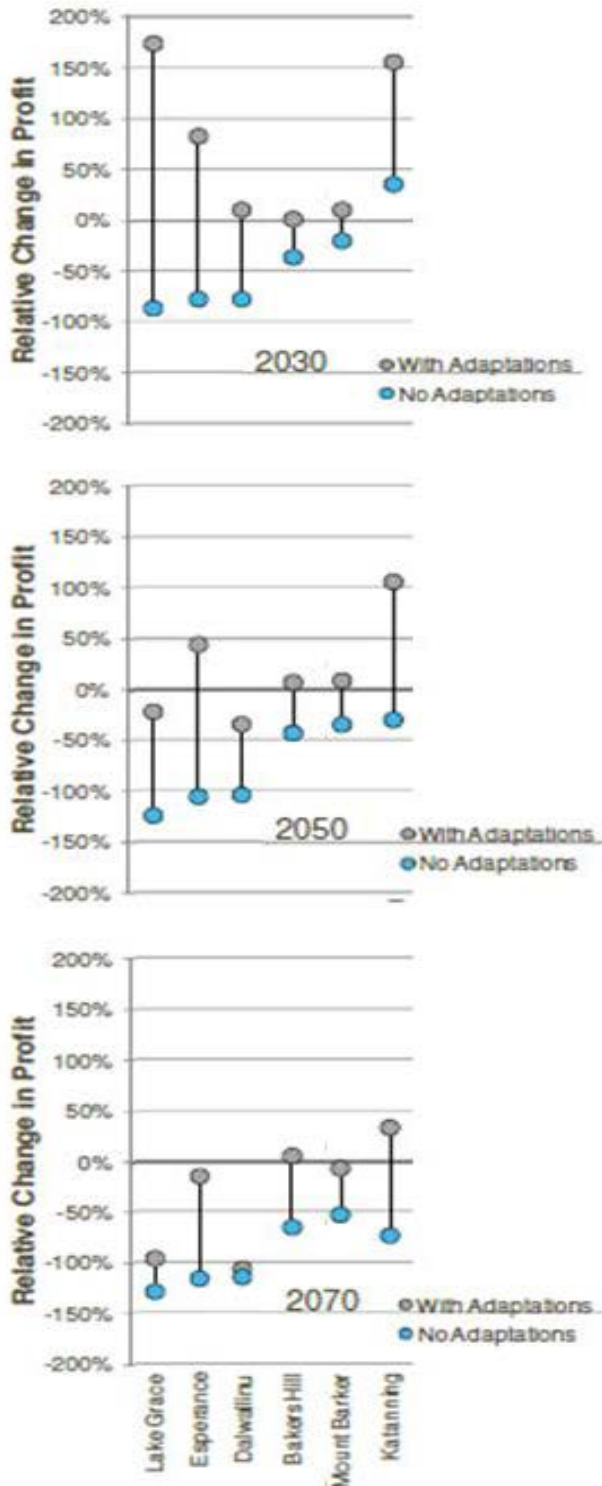


Figure 5.5 Average change in the profitability of Merino ewe enterprises resulting from climate changes projected by four global climate models under the SRES A2 scenario at six localities in WA. Values represented by blue circles are without any adaptive measures and grey circles are with the best available locally specific combination of adaptive measures. Values shown are changes relative to 1970–99 base scenario and are estimated using optimal sustainable stocking rates; 0% = no change, less than 100% = operating at a loss (SLA2030 2012a, 2012b)

Adaptations centre on:

- improving pasture water use efficiency, such as soil amelioration and species selection
- improving livestock performance, such as species and breed selection
- grazing management to improve utilisation and overcome the autumn feed gap, such as fodder conservation and confinement feeding
- use of decision support tools, such as forage production models, remote sensed data and long-range weather forecasts
- enterprise diversification.

Appendix D describes these and other adaptations in more detail.

Individual adaptations, such as improving soil fertility and increasing the area sown to lucerne, could maintain livestock enterprise profitability to 2030 in high rainfall areas, but combinations of adaptations would be needed in low rainfall areas of the eastern and northern wheatbelt (SLA2030 2012b; Ghahramani & Moore 2013). By 2050 and 2070, livestock production in the low rainfall parts of the agricultural zone may require new technologies, a complete re-thinking of the feed base or sustained improvements in terms of trade to remain viable (SLA2030 2012b; Ghahramani & Moore 2013). Where there is sufficient summer rainfall, summer active perennials or ephemerals, such as lucerne or *Cullen cinereum* and *C. graveolens*, could expand the feed base to provide green feed at times when the quality and quantity of dry feed is limited (Ghahramani & Moore 2013; Nicol et al. 2013).

John et al. (2005) used the crop and pasture simulation models APSiM and TACT and the economic model MUDAS (Model of an Uncertain Dryland Agricultural System) to investigate optimal farming systems for the Merredin region between 2000 and 2030. They found that without agronomic and technological advances, climate change might make farming in the region 80% less profitable. The area devoted to cropping and the stocking rates declined, the amount of supplementary feed required for the remaining livestock increased and there was a small increase in the area allocated to perennials such as lucerne, saltland pastures and oil mallees.

Abrahams et al. (2012) used the Simulated Transitional Economic Planning (STEP) model to examine the financial effect of production or system changes on farm businesses in the Northern Agricultural Region over time. This region has been identified as an area particularly vulnerable to the impacts of climate change. Abrahams et al. (2012) found that in the lowest rainfall areas (region L1 in Figure 5.4) the current crop-dominant, mixed farming systems could become economically unviable in 20 years. They suggested that moving to a system combining trade cattle (through a pastoral alliance), carbon farming and opportunistic cropping might improve viability by reducing risk in low rainfall years. Current cropping systems could remain viable in the medium and high rainfall areas (regions M1 and H1, respectively) if producers continue to have access to improved crop varieties (including lupins and canola) and technologies that support the profitable growing of crops.

Carmody et al. (2010b) suggested that producers in the low rainfall areas of the Central and Northern agricultural regions will become more opportunistic croppers and that farms would become larger and less intensive, with reduced returns per hectare and with less investment in on-farm and off-farm infrastructure. Turner et al. (2011) suggested that cropping is already opportunistic at the drier, eastern edges of the wheatbelt and an increasingly dry and variable climate may force producers to abandon cropping and become reliant on livestock, perhaps using new perennial fodder species.

A survey of farms in the North-eastern Agricultural Region found that producers classified 8% of cleared land producers as consistently unproductive, with the area expected to increase to 36% if the climate continues to dry (Blake et al. 2012). Blake et al. (2012) considered that even with agronomic adaptations, these soils would remain unprofitable with the survey indicating that 75% of producers would be willing to permanently revegetate consistently unproductive soils if they received financial support to do so.

Farquharson et al. (2013) set out a more transformative path to adaptation. They suggested that the introduction of perennial pasture legumes and mallee agroforestry systems into conventional wheatbelt farms would maintain farm income at Cunderdin and Katanning through to 2052 under an A2 emission scenario. However, this study only used the output from one global climate model as the basis for its analysis and that model projected that Katanning would be wetter in autumn and winter, which is at odds with the aggregate BoM and Indian Ocean Climate Initiative projections. John et al. (2005) also suggested the use of perennial plants, such as oil mallees and saltland pastures, could increase slightly as their deep roots and ability to survive dry periods equip them to cope with a drier climate. However, they warned that the capacity of producers to adopt new technologies, especially those requiring relatively large upfront capital investment such as oil mallees and saltland pastures, may be constrained by substantially lower profits from conventional activities.

Farquharson et al. (2013) point out that the profitability of mallees depends on the development of regional harvest, processing and transport facilities and a farm price and cost structure that is competitive with conventional agricultural activities. It is worth keeping these warnings in mind more generally as any analysis that uses modelling relies on assumptions about the degree of future climate change, crop and pasture response to climate variables and enterprise costs and earnings. In this case, Farquharson et al. (2013) used the output from the CSIRO Mark 3.5 (S2) global climate model to generate weather data, APSiM and GrassGro to generate crop and pasture growth data, and the Model of an Integrated Dryland Agricultural System (MIDAS) and Imagine analyses spreadsheet to estimate enterprise profitability.

Suggestions of moving towards more mixed farming systems in marginal areas, particularly systems with novel crops deriving income from carbon sequestration or bioenergy, are at odds with the adaptations seen to date. The current move to farming systems with a greater focus on more profitable cropping activities is a response to changing terms of trade rather than to a drying climate (Kingwell et al. 2013). Grundy et al. (2016) suggest there will be little change in land use unless

substantial global efforts to mitigate carbon emissions increase the price of carbon offsets above \$50 per tonne and increase demand for biofuels. Under this scenario (analogous to RCP 2.5) and starting around 2030, increasing areas of agricultural land in the south-west would be turned over to carbon and environmental plantings and to producing biofuels and bioenergy. Grundy et al. (2016) suggest the least productive agricultural land will change first, that there will be a greater effect on grazing land compared to cropping land, and that productivity improvements will see agriculture production increase despite the decline in area farmed.

Several studies have stressed the importance of producers' terms of trade in determining the future economic impacts of climate change and consequent adaptation strategies (Abrahams et al. 2012; Hertzler et al. 2013; Kingwell et al. 2013; Grundy et al. 2016). Modelling and analysis of historical global production data suggest that cereal production declines by 6–7% for each 1°C increase in average temperature (Asseng et al. 2015; Lesk et al. 2016). A 6% reduction in global wheat production amounts to a quarter of the global wheat trade in 2013 (Asseng et al. 2015). If, as projected, global grain yields decline with adverse climate change, grain prices — and by implication, prices for agricultural commodities generally — are likely to rise (Hertzler et al. 2013; Nelson et al. 2014). Increased prices may compensate for any yield decrease or increased risk associated with climate change in WA and facilitate continued cropping in areas that are currently considered marginal or an increase in cropping elsewhere (Hertzler et al. 2013).

However, Browne et al. (2013) found that rainfall had a greater impact on profitability than commodity prices. This study examined the profitability of a range of wool, prime lamb, cow–calf, steer, dairy, wheat and canola enterprises in the greater than 600mm annual rainfall zone of Victoria under low, average and high rainfall and commodity price scenarios. Wheat, steer, prime lamb and wool enterprises were least affected by low rainfall, dairy was the most profitable land use under average and high rainfall conditions, and dairy, canola and cow–calf enterprises were the least profitable under low rainfall conditions (Browne et al. 2013). The study suggests that the impacts of future climate change could be moderated by managing the enterprise mix on farms.

Various types of insurance can also mitigate climate risk. An expensive form open to individual businesses is to spread the risk geographically by owning farms in different locations (Hertzler et al. 2013). WA producers are now able to get multiperil crop insurance, with the insured value based on yields over the previous five years. Index insurance, based on insuring against particular climate or weather events (such as an El Niño event), is being piloted in other countries (Hertzler et al. 2013). The insurance market may become a more important driver for climate change adaptation over time (Booth & Williams 2012).

The decision facing land managers and policymakers is whether to continue to make incremental changes, take pre-emptive adaptive action or to respond reactively after the impacts are evident (Marshall et al. 2013). The risk with incrementalism is that climate changes and their impacts may be nonlinear or have tipping points or step changes that cause social, economic or ecological conditions to become so untenable that incremental changes will be ineffective (Rickards & Howden 2012;

Marshall et al. 2013). Continued investment in incremental adaptation to this point can limit the range of alternative pathways for change (Rickards & Howden 2012).

Despite this risk, and given the success of incremental change in WA to date, there is merit in Asseng and Pannell's (2013) view that it is prudent for most producers to wait and see what happens with future climate and technological developments before making transformational changes to their businesses.

5.2 Horticulture

Summary

- Changes in horticultural production associated with future climate change will depend on location, soil type and management. These changes will affect profitability and financial risk associated with farming enterprises, particularly in areas at the margins of enterprise suitability.
- Decreased annual rainfall will decrease groundwater recharge and increase variability in dam storage volumes in the southern half of WA. Adaptation will require:
 - improvements in irrigation practices
 - appropriate water policy
 - changes in crop variety and species to reflect water cost and availability.
- Increased temperatures will see the matching of appropriate climatic areas to crop type become increasingly important, particularly for long-lived perennial crops and those requiring a high degree of chilling:
 - the area suitable for growing tropical and subtropical crops may expand and the area suitable for temperate crops may contract.
- Attracting investing in long-lived, climate-dependent agricultural assets, such as irrigation infrastructure, vineyards and agroforestry, may become more difficult.
- The south-west will remain suited to producing high quality grapes and wine.
- Carnarvon will remain suited to producing bananas until at least 2030, but it may become too warm for banana production at Kununurra.
- At Manjimup, increased temperatures will allow alternative crops such as capsicum to be grown, and extend the growing season of some varieties but preclude the growing of others.
- At Gingin, increased temperatures will mean that more heat-tolerant lettuce cultivars will need to be introduced if summer production of lettuces is to continue after 2030.

As with broadacre farming, changes in horticultural production associated with future climate change will depend on location, soil type and management. These changes will affect profitability and financial risk associated with farming enterprises, particularly in areas at the margins of enterprise suitability. Rogers (2013) identified

the following as the most promising immediate actions that producers can take to minimise the impacts and prepare for the future:

- increasing water use efficiency and profitability
- selecting varieties that will grow in the changed climate
- adapting planting times or production slots in regions
- protecting crops by growing in greenhouses or under shade
- using irrigation to manage frost and high temperature spikes
- reducing electricity use for irrigation
- reducing electricity use for cooling and generating renewable power on-farm
- reducing on-farm emissions (mitigation).

Appendix E describes these and other actions in more detail.

Decreased annual rainfall will almost certainly continue to decrease run-off and groundwater recharge and increase variability in dam storage volumes in the southern half of WA. Where water resources are fully utilised or declining, adaptation strategies include:

- increasing water use efficiency
- water trading
- developing alternative sources of water
- moving demand to where water is available (Department of Water 2014b).

Morgan et al. (2008) identified access to water as the single biggest concern that producers had in relation to future climate change, with producers expressing concern about their ongoing capacity to grow crops and water their livestock. Regions most likely to be affected by climate change impacts on water availability and demand include Greenough, Moore, Perth, Peel and Preston (Thomas 2008). In these areas, there needs to be significant gains in water use efficiency and the development of alternative water supplies, including desalination, water re-use or substantial new inter-regional transfers into the metropolitan area (Thomas 2008).

For producers, improvements in irrigation practices and water policy will be required to successfully deal with climate change (Appendix E). For example, drip irrigation reduces the amount of water lost through evaporation and the amount of fertiliser lost via run-off and leaching, which can result in substantial savings in water use and operating costs.

The availability and cost of water is likely to become increasingly critical for farm viability in a drier future climate. Where the cost of water increases it may be possible to change the crop or enterprise type and improve the financial return per unit of water used (Figure 5.6).

There is likely to be increased pressure for access to water entitlements where dryland farming can be converted to irrigation, or where water can be used to

maintain the viability of animal production (Thomas and Sadler 2008). The development of water markets and water trading and the greater recognition of environmental water reserves could see the transfer of water from the production of low-value staple food crops to high-value horticultural activities and/or the environment or urban uses, with the potential to reduce staple food production (Qureshi et al. 2013).

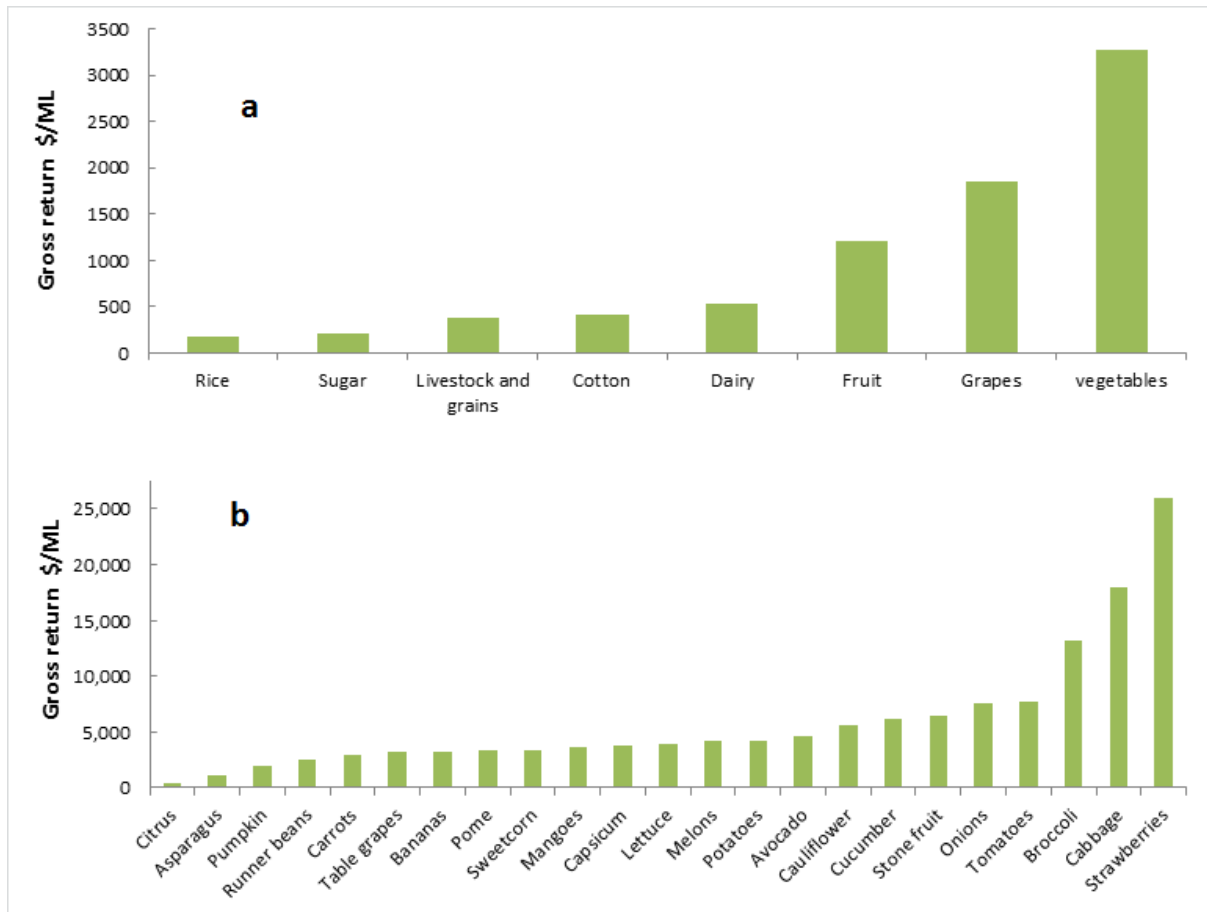


Figure 5.6 Gross return (dollars per megalitre [\$/ML]) from (a) various agricultural land uses in Australia in 2001 (Hickey et al. 2006), and (b) various vegetables and fruits in WA in 2007–08 and 2010–11 (Fazakerley & Windsor 2013)

Changes in water availability may be less of an issue for new and expanding irrigation areas in the north of WA, but temperature changes in absolute terms are expected to be greater in the north compared to the south. Consequently, the matching of appropriate climatic areas to crop type will be increasingly important, particularly for long-lived perennial crops (Webb & Whetton 2010). Climate change may expand the area suitable for growing tropical and subtropical crops and reduce the area suitable for temperate crops with high chilling requirements (Webb & Whetton 2010).

New varieties and improved technology and management techniques may need to be adopted in response to a warmer, drier climate (Appendix E). Rogers (2013) identified capsicum, beans, lettuce, cauliflower, broccoli, baby leaf spinach and rocket

as all having active breeding programs with a high probability of producing heat-tolerant varieties, although these may not be available in the short to medium term.

For some industries, such as wine production in the south-west, the impact of climate change may be relative small. Ward (2009) found that existing grape varieties are expected to remain suitable, with climate change increasing the suitability of newly planted varieties, though adaptive management will be required for the more sensitive aromatic whites. For other industries, it may be possible to adapt by changing the crop variety.

Long-term drought conditions in eastern Australia and the impact on irrigation enterprises and the environment have catalysed legislative and regulatory changes that improve:

- the clarity of property rights for water entitlements
- the ability to trade water entitlements and allocations
- recognition of the need for environmental flows (Meyer & Tyerman 2011).

Proposed reform of water resources legislation in WA should deliver similar outcomes. Bennett and Gardner (2014) identified the need for WA to broaden regulatory coverage, improve groundwater planning and promote flexible water access entitlements to ensure sustainable groundwater extraction rates in a drying climate and to increase the use of water markets to promote the productive and efficient use of groundwater. In 2004, the Council of Australian Governments agreed to form a National Water Initiative to implement a transparent planning framework that avoids over-allocation of water resources and considers the risks associated with climate change and variability in developing water management plans.

In addition to legislative and regulatory changes, adaptation will improve irrigation technology, management, water productivity and reduce off-site effects of drainage and groundwater pollution (Meyer & Tyerman 2011; Western Australian Government 2012). Together these adaptations should include:

- moving to water pricing that reflects the true cost of water
- removal of uncertainty related to water allocation and low water availability, including restricted water allocations to limit irrigation of poor returning crops
- research and extension to assist producers to better use water, including provision of accurate, accessible and useful water information at different scales
- improvements to water distribution and irrigation application systems, such as conversion of surface irrigation systems to drip and sprinkler systems
- further reduction of barriers and distortions to water trading
- optimising the environmental water allocation and seeking synergies between environmental and irrigation water allocations
- water supply authorities consolidating irrigation areas by improving water supply systems to improve the cost effectiveness of investments in water supply infrastructure

- facilitating carryover and capacity-sharing at larger scales.

Assessing the vulnerability of large, long-term investments, such as establishing perennial horticultural crops or irrigation infrastructure, will become more critical and more difficult in the face of climate impacts (Kingwell 2006).

Any increase in storm or tropical cyclone intensity will increase the risk of flood and erosion damage to infrastructure and soils and direct damage to horticultural crops. Tropical cyclones have had devastating effects on the Queensland banana industry (Web & Whetton 2010) and flooding has severely affected horticulture along the Gascoyne River in WA. The risk of smoke taint of wine grapes is likely to increase as bushfire risk increases in the future (Webb et al. 2010). Producers may also face increased energy costs as temperatures increase energy requirements for activities such as post-harvest chilling (Webb & Whetton 2010).

A set of linked strategies for irrigation practices and water policy, based on experience and potential opportunities, may lead to robust agricultural production with sustainable environment outcomes under a drier climate (Appendix E). However, producers are likely to face additional costs of capital adjustment because of climate change. Consequently, attracting investment in long-lived, climate-dependent agricultural assets, such as irrigation infrastructure, vineyards and agroforestry, may become more difficult (Kingwell 2006).

5.3 Pastoral industries

Summary

- Changes in productivity and water availability are likely to put some pastoral areas under severe financial and environmental stress:
 - the Pilbara and southern rangelands are most at risk.
- Unless there is a marked improvement in pastoralists' terms of trade, they may be faced with needing to make greater adaptations than other sectors. It is likely that incremental adaptation will not be sufficient and more transformative changes will be required.
- Adaptations include:
 - increasing efficiency of rangeland utilisation to improve rangeland condition and productivity
 - shifting to more heat-adapted livestock breeds and species
 - diversifying on-lease land uses, such as:
 - tourism
 - carbon farming
 - irrigated fodder production and confined feeding cattle before marketing.
 - off-farm income.

Livestock industries in the Pilbara and Southern Rangelands regions of WA are already challenged with deteriorating terms of trade, reduced carrying capacity, loss of human resources and climate change. In some areas, pastoralism is probably no longer economically, socially or environmentally sustainable (Safstrom & Waddell 2013). Most of these regions show some degree of environmental degradation: 24% (20.2 million hectares) is in poor or very poor condition and 30% (25 million hectares) is in fair condition (Safstrom & Waddell 2013). Continued unsustainable production will result in loss of biodiversity, a reduction in ecosystem services such as water and nutrient cycling, and loss of soil (Safstrom & Waddell 2013).

Even with the adoption of adaptation strategies, such as those listed in Appendix F, it may be beyond the capacity of individual producers to adapt to long-term reductions in livestock carrying capacity and increased climate variability. Without significant improvements in their terms of trade, climate change could result in financial and human distress (Miller & Burns 2008; Satore et al. 2008) and long-term damage to the resource base (McKeon et al. 2009).

Safstrom & Waddell (2013) suggest that there is potential for a transition to multifunctional land uses to bolster economic and social sustainability and allow the opportunity for landscape restoration in areas of the rangelands with opportunities for alternative on-lease and off-lease income. However, where economic viability is unattainable and producers are locked into a cycle of poverty, then lease buy-back and alternative management structures may be the only options.

As our understanding of the climate system and its likely impacts on WA's livestock systems and adaptation options improve, there is a major challenge of communicating this complexity to producers so they can apply adaptation strategies to minimise the negative impacts of climate change on the environment, agricultural production, and animal production and health (Black et al. 2008).

5.4 Intensive livestock industries

Summary

- There are incremental adaptations available for the sector to deal with climate variability and change in the short to medium term.
- Increasing energy efficiency is a priority as energy costs and cooling requirements increase.
- Improving water use efficiency, particularly irrigation efficiency, will become increasingly important.

Where animals are confined to sheds, climate change impacts on production systems may be relatively minor because there is greater opportunity to control environmental conditions (Rotter & van de Geijn 1999; Miller et al. 2010). In this situation, the effects of heat stress can be minimised by modifying the animals' environment to reduce heat loading (such as shade, misters, or pad cooling), nutritional manipulation (including changing feeding frequency, timing or energy density) and/or selection for heat tolerance (Appendix G; Henry et al. 2012). However,

water, feed and power will continue to be of concern, particularly where climate change affects price or availability. There is considerable scope for incremental adaptations in energy and water use efficiency for these enterprises (Appendix G).

For industries such as dairying, where producers grow feed that is grazed in the paddock, many of the adaptations relating to irrigation efficiency suggested for the horticultural sector, and management suggested for pasture and livestock in the broadacre livestock sector, are relevant. Dairy Australia (2015) suggests that there are a number of on-farm strategies to deal with climate change, but dealing with climate variability will remain the greatest challenge and is the issue that dairy producers should concentrate on rather than long-term climate trends. This advice may be more broadly applicable to the intensive livestock sector.

5.5 Planning for fire risk

The Mid West Regional Council, comprising the Carnamah, Coorow, Mingenew, Morawa, Mullewa, Perenjori and Three Springs shires, have identified bushfire management as their highest priority climate change risk (Nash et al. 2010).

The recognition of current and future climate change, a commitment to science, practical experience, adaptive management and willingness to reform legislation and policy should form the basis for the future development of fire management and emergency response in WA (Keelty 2011; Burrows & McCaw 2013).

Current fire risk systems are semi-empirical models, based largely on observations of ignition probabilities and fire spread under current climate and fire weather conditions. They may not be capable of modelling fire behaviour under future conditions (Sommer et al. 2014). Consequently, fire management will need a better understanding of fuel dynamics, fire behaviour and ecosystem responses in a warmer, drier climate (Nash et al. 2010; Burrows & McCaw 2013).

Changing climate will continue to alter the timing of and reduce the opportunity to undertake fuel reduction burning. Consequently, there will need to be a move away from landscape-scale burning towards the strategic use of fuel reduction burning in high-risk areas. In addition, new methods to reduce fuel loads will need to be developed (Nash et al. 2010; Keelty 2011; Hughes & Steffen 2013; Enright & Fontaine 2013).

In the highly fire-prone northern savannas and rangelands, strategic early season fuel reduction burning can reduce the risk of late season fires that are more intense. Early season burning has enterprise productivity and environmental benefits including reducing the emission of greenhouse gases and providing the opportunity to generate income from abatement credits (Sudmeyer et al. 2014).

Agricultural enterprises will need to undertake risk assessments to determine the future insurance liability presented by more frequent and severe bushfires (Nash et al. 2010).

6 Adaptive capacity and producers' attitudes

Summary

- The capacity of individual farmers to adapt to climate change may be vital to their future business success.
- An assessment of the capacity to adapt should consider what are termed the five capitals:
 - human: farmers' attitudes and skills
 - social: social networks and access to information
 - natural: land capability and access to resources
 - physical: infrastructure and technology
 - financial: including on-farm and off-farm income and debt.
- Understanding farmers' attitudes to climate change is critical to the success of any attempt to improve adaptive capacity:
 - for some farmers, information is best framed in terms of business and profitability rather than climate change
 - in all cases, information must be locally relevant, framed within the local socio-cultural, economic and biophysical context and delivered by locally credible sources.

The capacity of individual producers to adapt to climate change may be vital to the future success of their business. In some situations, a critical mass of individuals changing their practices may be needed for an industry-wide response to occur (Marshall et al. 2013). Marshall et al. (2013, p. 31) described this capacity at the individual level as having:

- the [ability to] manage the risks of change,
- the level of skills in planning, learning and reorganising,
- the level of financial and psychological flexibility to undertake change, and
- an interest in undertaking change.

In assessing adaptive capacity, it is important to consider how vulnerable agricultural enterprises are to structural adjustment pressures. Besides productivity changes associated with climate change, these pressures include declining terms of trade, technology-induced productivity changes and productivity changes associated with changes in the natural, economic and social resource bases (Nelson et al. 2005). These are defined as the five capitals:

1. human: producer education, experience, age, health, attitude to change, business skills and skilled labour
2. social: sense of community, access to information, access to services, family unit and producer networks
3. natural: soil, water resources, climate, natural resource capability, pests

4. physical: transport infrastructure, plant and machinery, technology, genetics, regional infrastructure
5. financial: off-farm income, land value, cost of production, equity–debt ratios, business management (Nelson et al. 2005; Fisher et al. 2014).

Australian research highlights the complexity of interactions among these five capitals. Dowd et al. (2014) found that producers making transformational changes had strong access to knowledge but had weak social ties, which facilitated their ability to plan and implement novel strategies and options outside the established social norm. Producers with stronger social network connections to family, friends and colleagues were less inclined to make radical changes and tended to make smaller incremental changes.

Nelson et al. (2005) used ABARE's annual farm survey data from 1992–93 and 2001–02 to assess these five capitals for Australian farm households, their relative exposure to external events and their internal capability to cope with those events. They identified the regions that were most vulnerable to structural adjustment pressure. This assessment is a snapshot in time but shows how vulnerabilities that influence producers' abilities to respond to climate change vary by region and industry sector (Figure 6.1).

Community consultation in WA showed that while there is broad recognition that the climate changed between 1970 and 2006, participants attributed much of that change to natural climate variation (Morgan et al. 2008). Over this period, the agricultural sector improved productivity with the principle driver being the need to maintain productivity and profitability in the face of ongoing climate 'variability' and evolving technology and market conditions, rather than responding to a perception of climate change (Morgan et al. 2008). The degree of producer concern about future climate change depended on where they farmed and while most felt able to cope, those from areas that are more marginal felt it would not take much change for farming to become unviable.

A 2008 survey of 255 WA producers found that 33% thought climate change was occurring and 31% regarded it as a major threat to the future of their business. However, just 19% believed climate change was caused by human activities (Evans et al. 2011). This question is interesting because it can be inferred that more producers are willing to acknowledge that the climate is changing if they do not need to attribute its cause to human activity. Importantly, only 33% of producers found climate change information easy to understand and they generally had concerns about the credibility of the science. Trust in the government was particularly low, with 50% of producers anticipating policymakers would be unfair or insensitive to the WA rural sector and only 8% thought the rural sector would be treated fairly (Evans et al. 2011). Reid (2010) suggested that for WA horticulturalists, the reasons they do not perceive climate change as a priority are encroaching urbanisation, existing pressures on water supplies, and many producers being close to retirement age and planning to sell their land rather than plan for the long term.

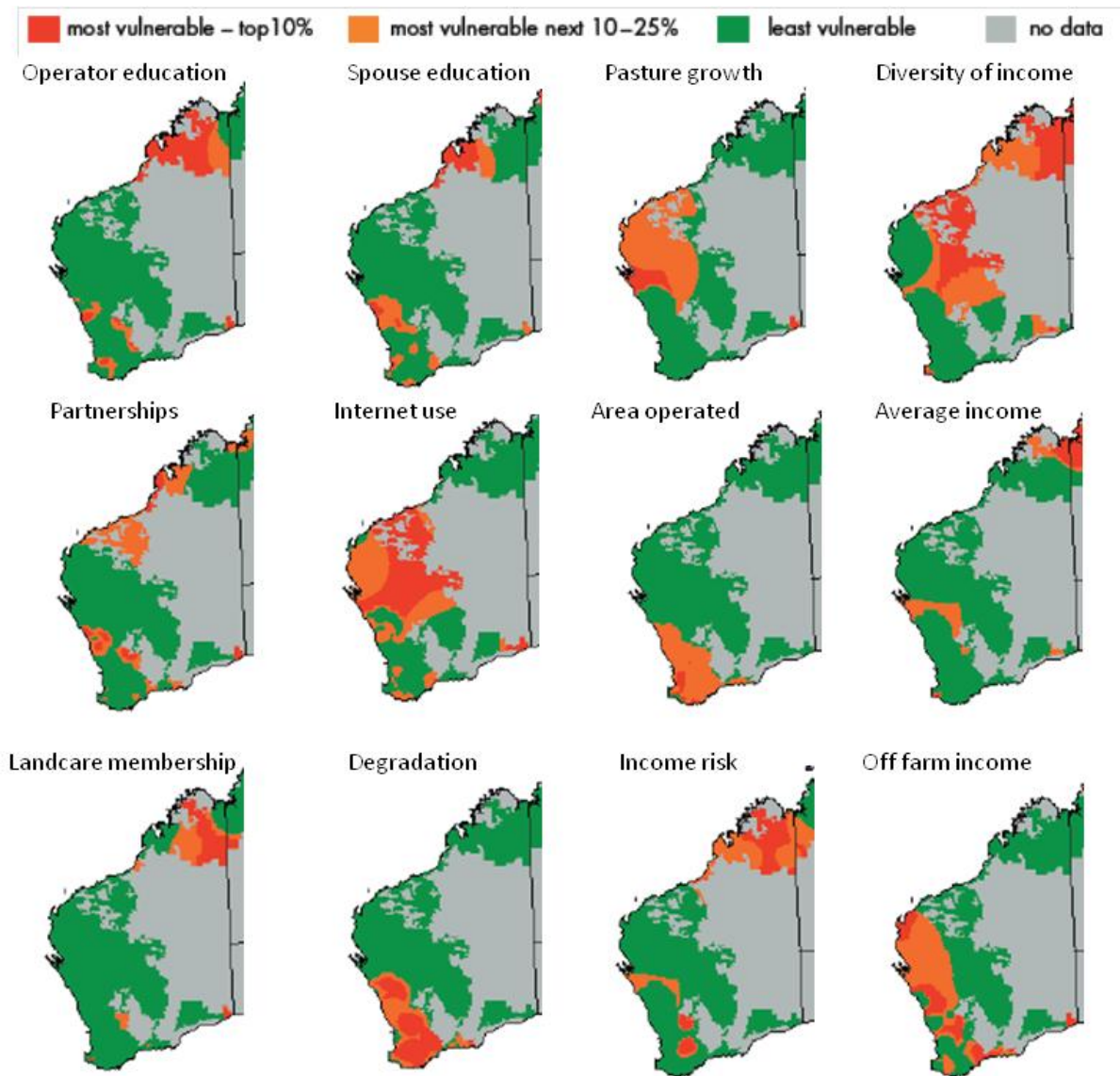


Figure 6.1 Factors contributing to the vulnerability of farms to structural adjustment (Nelson et al. 2005)

This ambivalence among primary producers in refuting the existence and causes of human-induced climate change while acknowledging that there are changes, variability or cycles in climate and drought, is widely held across Australia (Donnelly et al. 2009). Donnelly et al. (2009) suggest that regarding difficult climatic situations as just another period of drought or change in conditions that will eventually pass helps producers to avoid the sense of powerlessness and the inevitable negative impact on their business and lifestyle.

There appear to be two schools of thought on how best to deal with this ambivalence in producers' attitudes to changing climate. Evans et al. (2011) and Marshall et al. (2013) suggest it is necessary to improve climate change awareness within the farming community if adaptive capacity at an individual and industry scale is to be improved. While Donnelly et al. (2009) suggest the phrase 'climate change' should be avoided and any discussion should move beyond the issue of whether climate change is real or not and address the issues in terms of managing climate variability

from a risk management perspective. In its policy guidance paper, the National Climate Change Adaptation Research Facility (NCCARF 2012, p. 1) also takes this view, suggesting:

Information should be framed appropriately, for example in terms of business and profitability rather than climate change.

A survey of Queensland peanut producers found that producers with more climate change awareness tended to have greater adaptive capacity than those with limited awareness (Marshall et al. 2013). A national survey found producers' decisions to adopt sustainable land management practices are most influenced by financial concerns and to a lesser degree by environmental and personal motivations (Ecker et al. 2012). NCCARF (2012, p. 5) caution that "in the longer term, management for variability rather than change may deliver inappropriate, even maladaptive, solutions."

Reid (2010) emphasised the importance of providing horticulturalists with local climate data but noted that the lack of long-term temperature records hinders this provision and suggested that producers could be best engaged by discussing their concerns about water supply.

A series of climate change adaptation seminars and workshops run in 2007–08 for grape and wine producers from Margaret River, Pemberton and Mount Barker highlighted the importance of producing regional climate scenarios (Ward 2009). Innovative, fine-scale climate models were used to project past, current and future climates and researchers provided producers with the most up-to-date information about tools, technologies and management options that can be adopted or trialled by producers to adapt to climate change and variability. As a result, producers expressed a desire "to be kept informed, involved and engaged with researchers in their region in order to capture the opportunities and better manage the potential risks from a changing and variability climate" (Ward 2009, p. 40).

Galbreath (2015) attributed slower rates of climate change adaptation among WA wine producers compared to South Australian producers to greater exchange of knowledge in South Australia. These exchanges could be occurring on a peer-to-peer level but also through regional meetings, seminars, educational programs and specialised publications.

There is broad agreement that top–down approaches to improving climate change awareness are likely to be less successful than locally credible sources communicating locally relevant information framed within the local sociocultural, economic and biophysical context (Donnelly et al. 2009; Reid 2010; Evans et al. 2011; Marshall et al. 2013). Donnelly et al. (2009, p. 6) conclude:

A general communications strategy that is not locally relevant will fuel the existing misinformation between primary producers and will cement resistance to climate change action.....High impact communication will need to be emotionally engaging and address the benefits of mitigation and adaptation in terms of better risk management practices and improved farm profitability.

7 Future research, development and extension

Summary

- Increasing enterprise resilience to climate variability is widely considered the most important climate issue in the short to medium term.
- Climate change is broadly acknowledged as a long-term issue.
- There is a need for ongoing research, development and extension (RD&E) with some common themes:
 - climate projections at a local scale
 - systems-based research to continue delivering incremental adaptations for short- to medium-term climate variability and change
 - improved weather forecasting
 - understanding potential long-term impacts of climate projections on farming systems and broader industries.

The peak body for identifying and coordinating the climate change adaptation RD&E needs for the agricultural sector in Australia is the Climate Change Research Strategy for Primary Industries (CCRSPI). CCRSPI brought together government and industry leaders to develop a national RD&E strategy for climate change adaptation based around three outcomes:

- production systems based on the best available climate information
- lowering of greenhouse gas emissions intensity of products
- proactive participation in a carbon-constrained economy (Montague et al. 2012).

The strategy covers the period from 2012 to 2017 and while there is no mandate associated with its implementation, CCRSPI works to achieve the strategy outcomes by building on existing knowledge and experience, integrating with existing national and international activity and investments, communicating outcomes and RD&E activities and continuing to identify and advance its RD&E priorities. DAFWA is a CCRSPI partner, was involved in developing the plan and has an ongoing role in CCRSPI activities.

The information and links provided on the websites of various industry research and development and advocacy organisations shows there is considerable variation in the prominence given to climate-related issues but that there are also some common themes (Appendix H). Many sites provide information about projected climate and how it affects their particular sectors. While climate change is acknowledged as a long-term issue, increasing enterprise resilience to climate variability is identified as the most important climate issue facing producers across all sectors in the short to medium term. There appears to be a range of strategies and incremental adaptations currently available, but ongoing research is supported. Across the livestock sector, quantifying the greenhouse gas emissions intensity and identifying methods for reducing intensity is important. Emissions from livestock are the greatest source of greenhouse gas from the agricultural sector and understanding and reducing these

emissions is important for discussions about including the sector in greenhouse gas cap and trade schemes. An understanding also facilitates participation in voluntary carbon markets such as the Emission Reduction Fund. For the intensive livestock and horticultural sectors, increasing energy efficiency, reducing energy demand and generating energy on-farm (for example, by capturing and using methane released from animal manure) are methods of reducing the greenhouse gas intensity of products, reducing input costs and improving enterprise profitability. Horticulture and dairying identify improving irrigation efficiency as a central tool in dealing with a drying climate and the associated issues around water availability and price. Improving seasonal climate forecasts is a common research goal.

The NCCARF is a consortium comprising eight universities and the Queensland Government. It aims to:

- Identify the most important gaps in our knowledge and understanding about our vulnerabilities to climate change, and the possibilities for adaptation
- manage a portfolio of research projects that would address these gaps
- communicate the results from this research to policy makers and other end users to ensure their decisions about adaptation are based on the best possible information (NCCARF 2013, p. 1).

NCCARF operates across all sectors of the economy and engaged with the primary industries sector via the Primary Industries Adaptation Research Network.

NCCARF (2012) recognised that the community is already adapting to climate change and suggested that it is government's role to facilitate this process and to ensure that it is not maladaptive. NCCARF (2012) suggested that RD&E for the agricultural sector should focus on:

- improving productivity in water-limited environments
- developing an informed understanding of the limits to adaptation
- improving seasonal forecasting capability at regional and district levels
- improving forecasting of extreme events
- improving the availability of spatially explicit information on historical weather data, land use, vegetation, soils and topography to underpin adaptation decision-making
- maintaining an ongoing role for government to develop technologies, skills and awareness to create an information-rich industry through:
 - extension and education to ensure the best possible knowledge supports evidence-based decision-making
 - supporting networks to build industry-wide knowledge and skills
 - maintaining corporate knowledge in the industry.

DAFWA's Climate Change Adaptation Strategy (Bennett 2010) reflects these national guidelines and identifies five roles for DAFWA to assist industry to adapt and respond to climate change:

- provide leadership in the context of the Western Australian Government's policies and priorities
- raise awareness of climate change issues and provide information and training necessary for agribusiness to make informed decisions
- ensure climate change issues specific to WA are addressed through innovative responses including research and development
- provide policy advice and strategic analysis of climate change issues to government
- facilitate linkages between government agencies, research institutions and industry to deliver successful outcomes in climate change research and development and land-use planning.

A common theme of the RD&E guidelines and research papers reviewed here is that successful RD&E provides producers with locally relevant information and tools they need to make informed decisions about managing climate change impacts. Hayman et al. (2012) suggest that the questions that farm managers ask in relation to climate change can be categorised under four broad headings:

- climate projections at a local scale
- impacts of climate projections on existing farming systems
- adaptation options
- risks and opportunities from policies to reduce emissions.

Asseng and Pannell (2013) provided more-specific guidance in calling for WA research investment in the following areas:

- selecting and breeding to increase crop water use efficiency, heat tolerance and yield under high CO₂ conditions
- selecting and breeding new perennial species and cultivars adapted to future climates
- reducing the uncertainty of climate projections
- improving forecasts within seasons
- improving understanding of past and future impact of climate change on agriculture
- improving understanding of industry-wide consequences of climate change for resource management and conservation
- improving medium-term (three months) to long-term weather forecasting.

Asseng and Pannell's (2013) recommendations reflect the continuing need for low risk, applied research that provides incremental adaptations that are focused primarily on coping with climate variability (Figure 7.1). Howden et al. (2010b) share this view with the proviso that incremental adaptations need to be supported by monitoring of change and adaptation at a range of temporal, spatial and sectoral scales to maintain a flexible approach to policy and research. By also investing in improving the understanding of the long-term impacts of climate change, the potential pitfalls of managing for variability rather than change and delivering inappropriate or maladaptive solutions may be avoided (NCCARF 2012).

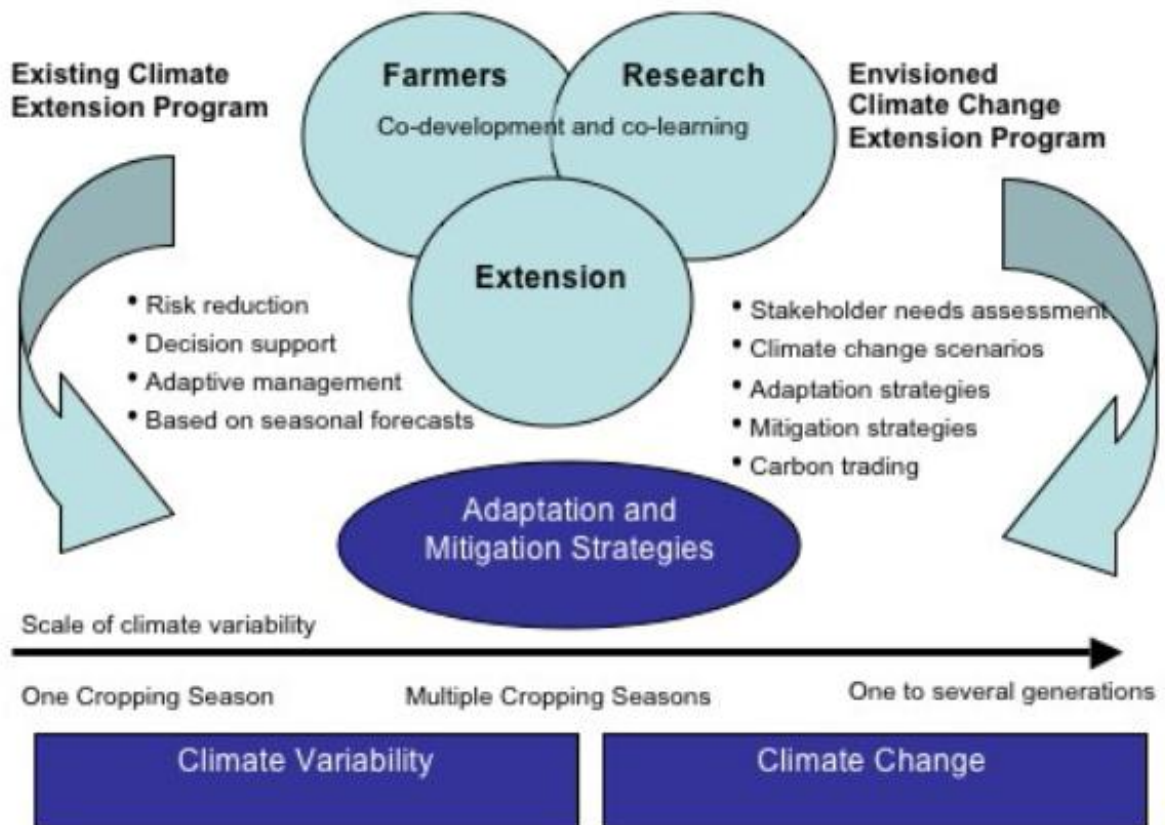


Figure 7.1 Relationship between climate variability, climate change and primary industry RD&E programs (Fraise et al. 2009)

Other authors have drawn on studies that have a spatial component to identify areas where the negative effects of climate change will be felt the most. For example, Moore and Ghahramani (2013) suggested that livestock and adaptation studies should focus on areas of the wheatbelt receiving less than 350mm annual rainfall.

There is broad consensus that RD&E activities should at least be conducted at the farming systems level rather than at the level of individual crop, soil or pasture sciences (Hayman et al. 2012). In addition to assessing eco-physiological impacts, vulnerability assessments also need to integrate some measure of the adaptive capacity of the sector or community to avoid reaching incorrect conclusions (Nelson et al. 2010). An assessment of the DAFWA-managed and delivered North-eastern

Agricultural Region strategy project (Burnside & Williams 2013, p. xii) highlighted this by concluding there:

There would seem to be a place for an overall RD&E program focused on ‘the science and practice of agriculture in highly variable and changing climates’ that invests in multidisciplinary work across biological, socio-economic and policy development disciplines.

A great deal of DAFWA’s RD&E work facilitates incremental adaptation to climate variability and declining rainfall (Figure 7.1). Where RD&E has been directed specifically at climate change adaptation or mitigation, it has been developed within the CCRSPI framework, has been externally funded and multidisciplinary in nature and often part of larger collaborations. This type of RD&E can be effective but expensive.

It has been suggested that a plateauing of crop yield (Figure 4.3) and the total factor productivity for farms since 2000 (Figure 5.3) can be attributed to the millennium drought and a long-term slowing of growth in public investment in agricultural research and development (ABARE 2010). If this is correct, it should be of great concern because we can expect climate change to put continuing and increasingly downward pressure on agricultural yield potential. This pressure will need to be addressed by incremental and transformative changes to agricultural practices that will need to be underpinned by increased investment in agricultural RD&E.

Appendices

A Confidence levels in projected climate changes

B Projected climate changes for Western Australia's natural resource management regions

C Adaptation options for the broadacre cropping sector

D Adaptation options for the broadacre livestock sector

E Adaptation options for the horticultural sector

F Adaptation options for the pastoral sector

G Adaptation options for the intensive livestock sector

H Climate change research and information provided by various agricultural sector peak bodies

Appendix A Confidence levels in projected climate changes

Table A1 Definition of confidence levels in projected climate outcomes (Mastrandrea et al. 2010; Stockler et al. 2013; CSIRO & BoM 2015)

Confidence level	Likelihood of outcome
Very high	90–100% probability
High	66–100% probability
Medium	33–66% probability
Low	0–33% probability

Appendix B Projected climate changes for Western Australia's natural resource management regions

Table B1 Projected changes in annual and seasonal climate variables in the Monsoonal North NRM region for the 2020–39 (2030) and 2080–99 (2090) periods, using CMIP5 global climate models and RCP 4.5 and RCP 8.5 relative to conditions during 1986–2005. Values are the median (50th percentile) change and 10th–90th percentile range (Hope et al. 2015; Moise et al. 2015; Watterson et al. 2015)

Variable	Season	2030 RCP 4.5 Median	2030 RCP 4.5 Range	2030 RCP 8.5 Median	2030 RCP 8.5 Range	2090 RCP 4.5 Median	2090 RCP 4.5 Range	2090 RCP 8.5 Median	2090 RCP 8.5 Range
Average temperature (°C)	Annual	0.9	0.6 to 1.3	1.0	0.7 to 1.3	1.8	1.3 to 2.7	3.8	2.8 to 5.1
	Summer	0.8	0.5 to 1.3	0.8	0.6 to 1.3	1.7	1.1 to 3.0	3.5	2.3 to 5.1
	Autumn	0.9	0.5 to 1.4	1.0	0.6 to 1.4	1.9	1.2 to 2.9	3.9	2.6 to 5.2
	Winter	1.0	0.5 to 1.4	1.1	0.7 to 1.4	2.0	1.5 to 2.7	4.2	3.2 to 5.3
	Spring	0.9	0.6 to 1.3	1.0	0.7 to 1.4	1.8	1.2 to 2.7	3.7	2.7 to 4.9
Max. temperature (°C)	Annual	1.0	0.6 to 1.3	1.0	0.7 to 1.3	1.9	1.3 to 2.9	3.7	2.7 to 5.0
	Summer	0.9	0.5 to 1.5	0.9	0.6 to 1.4	1.8	1.1 to 3.5	3.6	2.2 to 5.1
	Autumn	1.0	0.5 to 1.5	1.0	0.6 to 1.5	1.8	1.1 to 3.0	3.8	2.6 to 5.1
	Winter	1.0	0.5 to 1.4	1.1	0.7 to 1.4	2.0	1.3 to 2.7	3.9	2.9 to 4.9
	Spring	1.0	0.6 to 1.4	1.1	0.7 to 1.4	1.8	1.2 to 2.8	3.7	2.8 to 4.8
Min. temperature (°C)	Annual	0.9	0.6 to 1.3	1.0	0.8 to 1.3	1.9	1.3 to 2.7	3.9	2.9 to 5.2
	Summer	0.9	0.5 to 1.2	0.9	0.6 to 1.4	1.8	1.1 to 2.6	3.7	2.4 to 4.8
	Autumn	0.9	0.6 to 1.2	1.1	0.7 to 1.4	2.0	1.3 to 2.8	3.8	2.8 to 5.3
	Winter	1.0	0.6 to 1.4	1.1	0.7 to 1.4	2.1	1.4 to 2.8	4.2	3.4 to 5.5
	Spring	1.0	0.6 to 1.4	1.0	0.7 to 1.4	1.8	1.3 to 2.8	3.9	2.9 to 5.1
Rainfall (%)	Annual	0	–10 to 5	–2	–7 to 6	–1	–15 to 7	0	–24 to 24
	Summer	–1	–7 to 9	0	–7 to 9	0	–17 to 9	3	–24 to 20
	Autumn	0	–19 to 9	–3	–18 to 10	–1	–19 to 15	0	–31 to 32
	Winter	–7	–31 to 19	–11	–33 to 19	–18	–39 to 19	–15	–53 to 44
	Spring	–4	–26 to 18	–6	–23 to 14	–8	–30 to 29	–14	–46 to 30

Variable	Season	2030 RCP 4.5 Median	2030 RCP 4.5 Range	2030 RCP 8.5 Median	2030 RCP 8.5 Range	2090 RCP 4.5 Median	2090 RCP 4.5 Range	2090 RCP 8.5 Median	2090 RCP 8.5 Range
Windspeed (%)	Annual	-0.1	-2.4 to 0.7	0.2	-0.9 to 1.4	-0.4	-3.4 to 2.6	0.8	-3.7 to 5.1
	Summer	0.0	-3.7 to 2.6	1.0	-1.1 to 2.8	0.0	-3.3 to 4.6	1.9	-3.9 to 8.3
	Autumn	-0.6	-3.4 to 1.7	-0.6	-2.9 to 1.0	-1.6	-4.6 to 0.7	-3.3	-7.6 to 2.5
	Winter	-0.3	-4.2 to 2.7	-0.2	-1.5 to 3.1	-0.6	-5.0 to 3.8	0.4	-2.6 to 6.0
	Spring	0.6	-2.0 to 2.6	0.6	-1.1 to 2.4	1.0	-2.7 to 4.9	2.1	-0.5 to 8.4
Solar radiation (%)	Annual	-0.1	-0.8 to 1.1	0.0	-0.9 to 0.9	0.1	-1.5 to 2.0	-0.4	-3.1 to 1.8
	Summer	0.2	-1.8 to 1.7	-0.3	-1.9 to 1.6	-0.1	-2.3 to 3.7	-1.1	-5.0 to 4.3
	Autumn	-0.4	-2.0 to 2.4	0.0	-1.7 to 2.4	0.0	-2.7 to 2.9	-0.8	-5.1 to 2.7
	Winter	0.2	-1.1 to 1.5	0.3	-1.0 to 2.0	-0.3	-1.6 to 2.1	-0.9	-3.4 to 1.7
	Spring	0.3	-0.9 to 1.1	0.0	-0.8 to 1.4	-0.2	-1.4 to 1.4	-0.5	-2.6 to 2.0
Evapotranspiration (%)	Annual	2.9	1.6 to 4.3	3.1	2.3 to 5.1	6.5	3.9 to 8.6	12.4	8.3 to 16.7
	Summer	3.2	0.6 to 4.4	3.0	1.0 to 5.4	5.8	2.0 to 9.4	11.5	3.1 to 15.7
	Autumn	2.4	1.5 to 4.3	3.3	2.0 to 5.7	5.9	4.0 to 10.3	12.6	9.2 to 19.7
	Winter	3.3	1.0 to 5.4	3.7	1.2 to 5.6	7.3	4.7 to 9.4	15.3	8.4 to 19.5
	Spring	3.1	1.7 to 5.0	3.3	2.0 to 4.8	6.2	4.2 to 7.9	11.7	8.5 to 16.2
Soil moisture (%)	Annual	-0.7	-3.7 to 3.3	-0.8	-3.6 to 1.8	-0.9	-7.6 to 1.4	-2.6	-13.1 to 4.0
	Summer	-0.6	-5.7 to 5.4	-0.2	-5.5 to 3.6	-0.6	-13.9 to 4.2	-1.9	-22.4 to 7.1
	Autumn	-1.1	-8.1 to 5.5	-1.6	-7.1 to 4.9	-1.9	-10.3 to 1.5	-5.4	-20.8 to 3.9
	Winter	-0.2	-3.3 to 2.0	-0.3	-2.1 to 1.3	-0.7	-4.8 to 0.3	-1.5	-6.3 to 0.8
	Spring	-0.2	-1.3 to 0.6	-0.1	-1.1 to 0.7	-0.1	-1.4 to 1.7	-0.1	-3.8 to 4.9

Table B2 Projected changes in annual and seasonal climate variables in the Rangelands North NRM region for the 2020–39 (2030) and 2080–99 (2090) periods, using CMIP5 global climate models and RCP 4.5 and RCP 8.5 relative to conditions during 1986–2005. Values are the median (50th percentile) change and 10th–90th percentile range (Hope et al. 2015; Moise et al. 2015; Watterson et al. 2015)

Variable	Season	2030 RCP 4.5 Median	2030 RCP 4.5 Range	2030 RCP 8.5 Median	2030 RCP 8.5 Range	2090 RCP 4.5 Median	2090 RCP4.5 Range	2090 RCP 8.5 Median	2090 RCP 8.5 Range
Average temperature (°C)	Annual	1.0	0.6 to 1.5	1.1	0.8 to 1.5	2.1	1.5 to 3.1	4.4	3.1 to 5.6
	Summer	1.0	0.5 to 1.7	1.0	0.7 to 1.6	2.2	1.2 to 3.3	4.1	2.6 to 5.9
	Autumn	1.1	0.5 to 1.5	1.1	0.6 to 1.6	2.1	1.4 to 3.0	4.3	2.5 to 5.8
	Winter	1.0	0.7 to 1.5	1.1	0.8 to 1.6	2.1	1.5 to 2.9	4.4	3.3 to 5.4
	Spring	1.1	0.6 to 1.6	1.2	0.7 to 1.6	2.2	1.5 to 3.2	4.7	3.3 to 6.2
Max. temperature (°C)	Annual	1.0	0.6 to 1.5	1.1	0.8 to 1.5	2.1	1.5 to 3.1	4.4	3.1 to 5.6
	Summer	1.0	0.5 to 1.7	1.0	0.7 to 1.6	2.2	1.2 to 3.3	4.1	2.6 to 5.9
	Autumn	1.1	0.5 to 1.5	1.1	0.6 to 1.6	2.1	1.4 to 3.0	4.3	2.5 to 5.8
	Winter	1.0	0.7 to 1.5	1.1	0.8 to 1.6	2.1	1.5 to 2.9	4.4	3.3 to 5.4
	Spring	1.1	0.6 to 1.6	1.2	0.7 to 1.6	2.2	1.5 to 3.2	4.7	3.3 to 6.2
Min. temperature (°C)	Annual	1.0	0.6 to 1.4	1.1	0.8 to 1.5	2.0	1.4 to 2.9	4.3	3.3 to 5.6
	Summer	1.0	0.6 to 1.5	1.1	0.8 to 1.7	2.0	1.3 to 3.1	4.1	2.7 to 5.5
	Autumn	1.0	0.6 to 1.3	1.1	0.7 to 1.6	2.1	1.5 to 2.9	4.5	3.0 to 5.8
	Winter	1.0	0.6 to 1.4	1.1	0.7 to 1.5	2.0	1.3 to 2.9	4.2	3.3 to 5.3
	Spring	1.1	0.4 to 1.6	1.2	0.6 to 1.7	2.2	1.3 to 3.3	4.5	3.4 to 6.0
Rainfall (%)	Annual	-2	-11 to 7	-1	-11 to 8	-5	-16 to 9	-4	-31 to 19
	Summer	0	-12 to 8	0	-11 to 17	-3	-17 to 10	4	-21 to 26
	Autumn	-1	-24 to 22	0	-24 to 20	-2	-22 to 33	6	-40 to 39
	Winter	-7	-27 to 19	-10	-31 to 18	-11	-32 to 7	-22	-58 to 35
	Spring	-1	-25 to 22	-3	-20 to 13	-9	-32 to 12	-14	-53 to 26

Variable	Season	2030 RCP 4.5 Median	2030 RCP 4.5 Range	2030 RCP 8.5 Median	2030 RCP 8.5 Range	2090 RCP 4.5 Median	2090 RCP4.5 Range	2090 RCP 8.5 Median	2090 RCP 8.5 Range
Windspeed (%)	Annual	-0.3	-2.5 to 0.8	-0.1	-1.3 to 0.8	-0.5	-2.6 to 1.6	0.2	-4.8 to 2.4
	Summer	-1.2	-2.8 to 1.5	-0.6	-2.8 to 1.6	-1.4	-3.7 to 1.3	-1.0	-5.5 to 2.1
	Autumn	-0.8	-2.2 to 1.9	-0.6	-2.7 to 1.1	-1.2	-4.1 to 0.7	-1.2	-6.4 to 0.5
	Winter	0.3	-2.2 to 1.7	0.7	-1.5 to 2.3	0.2	-2.9 to 3.3	1.4	-2.2 to 5.6
	Spring	0.4	-1.7 to 1.6	0.3	-1.8 to 1.6	-0.2	-2.5 to 2.7	0.8	-3.8 to 4.5
Solar radiation (%)	Annual	0.0	-0.9 to 1.0	-0.1	-1.4 to 0.9	0.0	-1.4 to 1.5	-0.8	-3.3 to 1.2
	Summer	0.1	-1.7 to 1.5	-0.3	-2.1 to 1.1	-0.2	-2.2 to 2.2	-1.1	-4.6 to 1.5
	Autumn	-0.4	-2.5 to 2.1	-0.5	-2.7 to 1.7	-0.4	-2.9 to 2.5	-2.2	-6.4 to 1.7
	Winter	0.5	-1.3 to 2.4	0.4	-1.2 to 3.1	0.3	-1.3 to 3.8	0.4	-2.7 to 6.3
	Spring	0.0	-1.2 to 1.8	-0.3	-1.8 to 1.2	0.0	-1.6 to 1.7	-0.3	-2.3 to 1.2
Evapotranspiration (%)	Annual	2.4	1.1 to 4.5	3.0	1.4 to 4.2	5.1	3.3 to 8.4	11.7	6.7 to 17.7
	Summer	2.6	0.8 to 4.5	2.8	1.2 to 5.1	5.2	3.0 to 9.5	12.2	7.8 to 17.3
	Autumn	3.1	-0.9 to 4.9	2.6	0.1 to 6.0	5.7	2.3 to 10.2	13.8	6.1 to 20.4
	Winter	2.4	-0.2 to 5.5	2.3	-0.5 to 5.3	5.1	1.7 to 8.8	11.8	3.8 to 18.2
	Spring	2.8	-0.1 to 5.4	2.7	0.7 to 5.7	5.0	1.6 to 7.8	10.7	4.2 to 16.1
Soil moisture (%)	Annual	-0.2	-1.3 to 0.4	-0.3	-1.3 to 1.2	-0.4	-3.5 to 0.4	-1.0	-5.2 to 2.6
	Summer	-0.1	-1.3 to 1.3	-0.2	-1.6 to 2.2	-0.2	-3.6 to 1.6	-0.6	-6.3 to 3.9
	Autumn	-0.2	-2.7 to 2.2	-0.1	-1.7 to 2.4	-0.4	-2.0 to 2.0	-0.8	-6.5 to 3.2
	Winter	-0.7	-2.2 to 0.8	-0.5	-2.3 to 0.6	-1.4	-5.0 to 0.8	-2.0	-7.0 to 0.7
	Spring	0.0	-1.5 to 0.7	-0.4	-1.7 to 0.1	-0.1	-3.0 to 0.9	-0.3	-5.1 to 5.4

Table B3 Projected changes in annual and seasonal climate variables in the Rangelands South NRM region for the 2020–39 (2030) and 2080–99 (2090) periods, using CMIP5 global climate models and RCP 4.5 and RCP 8.5 relative to conditions during 1986–2005. Values are the median (50th percentile) change and 10th–90th percentile range (Hope et al. 2015; Moise et al. 2015; Watterson et al. 2015)

Variable	Season	2030 RCP 4.5 Median	2030 RCP 4.5 Range	2030 RCP 8.5 Median	2030 RCP 8.5 Range	2090 RCP 4.5 Median	2090 RCP4.5 Range	2090 RCP 8.5 Median	2090 RCP 8.5 Range
Average temperature (°C)	Annual	0.9	0.6 to 1.2	1.0	0.7 to 1.3	2.0	1.3 to 2.6	4.0	2.8 to 5.1
	Summer	1.0	0.6 to 1.5	1.0	0.6 to 1.4	2.1	1.4 to 2.9	4.0	2.5 to 5.2
	Autumn	0.9	0.5 to 1.3	0.9	0.4 to 1.5	1.9	1.1 to 2.5	4.0	2.6 to 5.1
	Winter	0.8	0.5 to 1.2	0.9	0.7 to 1.3	1.7	1.2 to 2.3	3.8	2.8 to 4.7
	Spring	1.0	0.6 to 1.4	1.1	0.6 to 1.5	2.1	1.5 to 2.7	4.3	3.2 to 5.4
Max temperature (°C)	Annual	1.0	0.7 to 1.4	1.1	0.7 to 1.4	2.2	1.2 to 2.8	4.3	2.8 to 5.2
	Summer	1.0	0.6 to 1.6	1.1	0.6 to 1.5	2.2	1.3 to 3.1	4.1	2.5 to 5.5
	Autumn	0.9	0.4 to 1.5	1.0	0.4 to 1.5	2.1	1.0 to 2.9	4.0	2.4 to 5.2
	Winter	1.0	0.5 to 1.4	1.1	0.6 to 1.6	2.1	1.2 to 2.6	4.3	3.0 to 5.1
	Spring	1.1	0.7 to 1.5	1.1	0.7 to 1.8	2.3	1.5 to 3.1	4.7	3.2 to 6.0
Min. temperature (°C)	Annual	0.8	0.6 to 1.2	1.0	0.6 to 1.3	1.8	1.2 to 2.4	3.8	3.0 to 4.6
	Summer	0.9	0.5 to 1.4	1.0	0.7 to 1.4	2.0	1.3 to 2.7	4.0	2.9 to 4.8
	Autumn	0.8	0.5 to 1.2	0.9	0.5 to 1.5	1.9	1.2 to 2.4	4.0	2.9 to 5.0
	Winter	0.7	0.4 to 1.1	0.8	0.5 to 1.3	1.5	1.0 to 2.2	3.5	2.7 to 4.4
	Spring	0.9	0.5 to 1.3	1.0	0.6 to 1.4	2.0	1.2 to 2.6	4.0	3.0 to 5.2
Rainfall (%)	Annual	-2	-14 to 7	-2	-10 to 8	-5	-19 to 7	-4	-29 to 13
	Summer	-1	-22 to 10	0	-15 to 16	-1	-24 to 12	-2	-24 to 21
	Autumn	0.0	-23 to 18	3	-23 to 26	0	-25 to 22	5	-42 to 29
	Winter	-5	-25 to 18	-5	-21 to 11	-7	-36 to 6	-16	-46 to 1
	Spring	-4	-18 to 17	-3	-20 to 20	-11	-26 to 15	-8	-53 to 23

Variable	Season	2030 RCP 4.5 Median	2030 RCP 4.5 Range	2030 RCP 8.5 Median	2030 RCP 8.5 Range	2090 RCP 4.5 Median	2090 RCP4.5 Range	2090 RCP 8.5 Median	2090 RCP 8.5 Range
Windspeed (%)	Annual	0.0	-1.3 to 0.9	-0.1	-1.2 to 1.0	-0.4	-2.0 to 0.8	0.7	-2.4 to 2.0
	Summer	-0.6	-2.1 to 1.5	-0.2	-2.9 -1.8	-0.7	-2.7 to 1.0	0.7	-4.2 to 4.0
	Autumn	-0.1	-1.5 to 2.0	0.0	-1.8 to 1.9	-0.5	-2.5 to 1.6	0.6	-3.7 to 2.4
	Winter	-0.1	-2.6 to 1.9	-0.3	-2.3 to 1.7	-1.1	-3.0 to 1.4	-1.4	-4.8 to 2.0
	Spring	0.2	-0.9 to 1.1	0.0	-1.2 to 1.1	0.4	-0.8 to 1.5	-0.3	-1.8 to 1.4
Solar radiation (%)	Annual	0.1	-1.4 to 1.7	-0.1	-1.8 to 1.2	-0.1	-1.9 to 1.7	-0.8	-3.3 to 1.1
	Summer	-0.1	-1.9 to 1.9	-0.7	-2.6 to 2.0	-0.3	-2.6 to 1.7	-1.4	-4.4 to 1.6
	Autumn	0.9	-0.8 to 3.2	1.0	-0.8 to 3.5	2.4	0.1 to 4.8	3.2	0.4 to 6.5
	Winter	0.3	-0.9 to 1.4	-0.1	-1.5 to 1.0	0.4	-1.3 to 1.9	-0.1	-2.2 to 1.7
	Spring	2.5	0.7 to 3.4	2.7	1.1 to 4.8	4.7	2.6 to 7.1	10.5	6.4 to 14.5
Evapotranspiration (%)	Annual	2.3	-0.2 to 3.8	2.9	-0.1 to 4.7	4.4	2.4 to 7.8	10.4	6.2 to 15.7
	Summer	2.7	0.5 to 5.2	3.3	0.7 to 7.2	5.7	3.8 to 9.6	12.9	9.2 to 19.4
	Autumn	2.4	0.7 to 6.1	3.1	0.5 to 5.5	5.9	2.6 to 10.1	11.7	6.4 to 19.6
	Winter	1.9	-0.2 to 4.0	2.4	0.2 to 3.7	3.2	0.2 to 6.2	7.1	4.3 to 12.0
	Spring	-0.8	-3.5 to 0.2	-0.7	-3.4 to 0.2	-1.5	-3.5 to 0.5	-1.7	-5.9 to -0.5
Soil moisture (%)	Annual	-0.2	-1.3 to 0.3	-0.1	-1.2 to 0.7	0.0	-1.2 to 0.7	-0.2	-1.6 to 0.7
	Summer	-0.8	-3.6 to 1.3	-0.4	-2.9 to 1.7	-1.0	-4.0 to 0.9	-1.0	-4.4 to -0.1
	Autumn	-1.5	-7 to -0.1	-2.3	-7.1 to 0.7	-3.4	-7.0 to 0.9	-6.1	-11.1 to -0.8
	Winter	-0.3	-1.9 to 0.1	-0.4	-2.3 to 0	-0.3	-2.3 to 0.4	-0.4	-4.8 to 0.9
	Spring	0.0	-1.3 to 0.9	-0.1	-1.2 to 1.0	-0.4	-2 to 0.8	0.7	-2.4 to 2.0

Table B4 Projected changes in annual and seasonal climate variables in the South-West NRM region for the 2020–39 (2030) and 2080–99 (2090) periods, using CMIP5 global climate models and RCP 4.5 and RCP 8.5 relative to conditions during 1986–2005. Values are the median (50th percentile) change and 10th–90th percentile range (Hope et al. 2015; Moise et al. 2015; Watterson et al. 2015)

Variable	Season	2030 RCP 4.5 Median	2030 RCP 4.5 Range	2030 RCP 8.5 Median	2030 RCP 8.5 Range	2090 RCP 4.5 Median	2090 RCP4.5 Range	2090 RCP 8.5 Median	2090 RCP 8.5 Range
Average temperature (°C)	Annual	0.8	0.6 to 1.0	0.8	0.5 to 1.2	1.7	1.1 to 2.1	3.5	2.6 to 4.2
	Summer	0.9	0.5 to 1.1	0.9	0.5 to 1.3	1.8	1.1 to 2.4	3.7	2.5 to 4.5
	Autumn	0.7	0.4 to 1.2	0.8	0.4 to 1.2	1.7	1.0 to 2.2	3.4	2.4 to 4.2
	Winter	0.7	0.4 to 0.9	0.7	0.5 to 0.9	1.5	1.0 to 1.8	3.1	2.3 to 3.8
	Spring	0.8	0.5 to 1.1	0.9	0.6 to 1.4	1.8	1.2 to 2.4	3.5	2.9 to 4.6
Max temperature (°C)	Annual	0.9	0.6 to 1.1	0.9	0.6 to 1.2	1.8	1.3 to 2.4	3.8	2.7 to 4.5
	Summer	1.0	0.5 to 1.3	0.9	0.6 to 1.3	1.9	1.1 to 2.6	3.8	2.5 to 4.6
	Autumn	0.7	0.3 to 1.3	0.8	0.4 to 1.3	1.7	1.0 to 2.5	3.6	2.2 to 4.4
	Winter	0.8	0.4 to 1.2	0.8	0.5 to 1.3	1.8	1.2 to 2.1	3.6	2.7 to 4.2
	Spring	0.9	0.6 to 1.4	1.0	0.6 to 1.6	2.0	1.4 to 2.7	4.0	3.1 to 5.1
Min. temperature (°C)	Annual	0.7	0.4 to 0.9	0.8	0.4 to 1.1	1.6	1.0 to 2.0	3.2	2.5 to 4.0
	Summer	0.8	0.5 to 1.0	0.8	0.4 to 1.3	1.8	1.1 to 2.3	3.6	2.6 to 4.4
	Autumn	0.7	0.3 to 1.2	0.8	0.4 to 1.2	1.6	1.0 to 2.3	3.3	2.5 to 4.3
	Winter	0.6	0.3 to 0.8	0.6	0.4 to 1.0	1.3	0.9 to 1.7	2.7	2.2 to 3.6
	Spring	0.7	0.4 to 0.9	0.8	0.4 to 1.2	1.6	1.0 to 2.2	3.2	2.5 to 4.1
Rainfall (%)	Annual	-6	-15 to -1	-5	-15 to 1	-12	-22 to -1	-18	-37 to -5
	Summer	-8	-31 to 17	2	-23 to 20	-4	-29 to 28	-5	-31 to 36
	Autumn	-4	-20 to 10	1	-20 to 17	-4	-26 to 12	-6	-32 to 13
	Winter	-7	-18 to 4	-9	-18 to 2	-14	-28 to -4	-29	-44 to -15
	Spring	-11	-23 to 4	-11	-28 to 4	-19	-36 to 1	-36	-59 to -14

Variable	Season	2030 RCP 4.5 Median	2030 RCP 4.5 Range	2030 RCP 8.5 Median	2030 RCP 8.5 Range	2090 RCP 4.5 Median	2090 RCP4.5 Range	2090 RCP 8.5 Median	2090 RCP 8.5 Range
Windspeed (%)	Annual	-0.1	-1.7 to 1.1	0.0	-2.0 to 1.9	-0.3	-2.6 to 1.4	0.3	-2.7 to 3.3
	Summer	0.3	-1.8 to 1.8	0.6	-1.3 to 3.6	-0.2	-2 to 2.3	2.3	-0.5 to 6.8
	Autumn	0.0	-1.6 to 1.7	1.0	-2.2 to 2.2	0.2	-1.9 to 1.9	1.2	-1.0 to 3.2
	Winter	-1.0	-4.9 to 1.9	-1.5	-4.2 to 1.4	-1.8	-8.0 to 2.1	-4.2	-9.3 to -0.3
	Spring	0.1	-1.7 to 1.6	0.0	-2.1 to 2.6	-0.4	-3.5 to 2.4	1.5	-2.6 to 5.1
Solar radiation (%)	Annual	0.6	-0.4 to 1.6	0.4	-0.6 to 1.6	1.0	0.0 to 2.1	1.0	-0.6 to 3.0
	Summer	0.1	-1.8 to 1.7	-0.4	-1.6 to 1.5	0.2	-1.9 to 1.4	-0.5	-3.0 to 0.8
	Autumn	0.2	-1.5 to 2.0	0.1	-2.1 to 1.4	0.6	-1.4 to 2.4	-0.5	-2.6 to 1.9
	Winter	1.6	-0.2 to 3.7	1.5	0.5 to 4.1	3.1	1.3 to 6.1	6.2	2.5 to 11.4
	Spring	0.8	-0.2 to 2.1	0.9	-0.3 to 1.9	1.5	0.3 to 2.9	2.2	0.5 to 5.1
Evapotranspiration (%)	Annual	2.5	1.2 to 3.5	2.8	1.5 to 4.3	5.4	3.4 to 7.2	10.3	7.1 to 15.2
	Summer	1.5	0.5 to 3.1	2.3	0.7 to 3.6	4.2	2.5 to 5.9	9.1	5.1 to 11.7
	Autumn	3.2	1.3 to 4.5	3.3	2.2 to 6.1	6.8	4.9 to 9.6	13.7	8.4 to 18.3
	Winter	4.3	1.3 to 7.3	4.4	2.5 to 7.7	9.8	6.2 to 14.3	18.6	12.4 to 30.5
	Spring	2.4	0.4 to 3.3	2.4	0.5 to 4.5	4.9	2.0 to 7.1	9.2	4.8 to 14.8
Soil moisture (%)	Annual	-1.5	-4.1 to -0.7	-2.0	-3.6 to -0.9	-3.1	6.0 to 0.3	-5.9	-12.4 to -3.0
	Summer	-0.3	-1.3 to 0.1	0.1	-1.1 to 0.5	0.0	-0.6 to 0.5	-0.2	-0.7 to 0.8
	Autumn	-1.3	-2.9 to 0.1	-0.6	-1.9 to 0.7	-1.3	-4.0 to 1.0	-2.2	-4.4 to -0.2
	Winter	-3.1	-7.8 to 0.0	-4.2	-7.4 to -1.4	-6.1	-9.7 to 0.2	-11.4	-20.7 to -6.4
	Spring	-2.6	-5.6 to -0.7	-2.9	-4.8 to -1.1	-3.8	-7.5 to -1.9	-6.7	-17.8 to -2.8

Appendix C Adaptation options for the broadacre cropping sector

Improve rainfall use efficiency of plants

Increase plant ability to access stored soil water

- Remove physical constraints to root growth
 - drainage to reduce waterlogging, such as deep drains, raised beds, surface drainage
 - deep-ripping to remove hard pans
 - gypsum to improve soil structure
 - controlled traffic farming to reduce compaction
 - increase soil organic carbon content, for example, by including perennial pasture phases or increasing stubble retention
- Remove chemical constraints to root growth
 - apply micronutrients and macronutrients
 - liming to increase soil pH
 - drainage to reduce sodicity
- Use crop varieties/species with increased ability to explore soil profile
 - root morphology (deep vs lateral roots)
 - tolerance of chemical soil constraints, such as pH, boron, aluminium and transient sodicity
 - ability to grow through soil physical constraints such as hard pans or transient waterlogging

Increase volume of plant available soil water

- Improve soil water-holding capacity
 - increase soil organic carbon content
 - reduced tillage
 - deep-ripping
 - gypsum to improve soil structure
 - controlled traffic farming to reduce compaction
 - claying (surface application/delving/spading) to reduce non-wetting
- Eliminate water use by weeds
 - fallows to increase stored soil water at the start of the growing season
 - summer (control summer weeds)
 - previous growing season (bare fallow, green or brown manures)
 - crop/pasture/fallow rotations
 - herbicide management
 - cultivation, such as strategic use of mouldboard ploughing)

- herbicide-tolerant crops
- improve weed germination by ameliorating non-wetting soil
 - claying (surface application/delving/spading), generally in high rainfall areas
 - application of surfactants, generally in medium rainfall areas
- chaff management
- crop canopy management
- Root rip along tree lines
- Reduce evaporation of soil water
 - reduced tillage
 - stubble retention
 - mulching
 - rapid crop canopy development/closure
 - reduce evaporation from soil by increasing deep infiltration of rainfall
 - furrow sowing
 - application of wetting agent to furrows
 - sow into previous years furrows (precision agriculture)
 - use of press wheels to increase run-off into furrow
- Reduce run-off
 - stubble retention
 - contour sowing
 - minimum tillage
 - claying

Use best adapted crop species and varieties

- Use crop varieties or species with increased drought resistance, such as stay-green varieties
 - Physiological tolerance of hot and dry conditions
 - ability to maintain cell turgor
 - stomatal resistance
 - crop varieties with long coleoptile (deep sowing)
 - shorter growing season
- Use varieties or species which are better able to exploit the fertilisation effect of increased atmospheric CO₂ to improve water use efficiency
- Use crop varieties or species that are bred to resist current disease risks and new risks presented by changing climate
 - Crop rotation for disease management

Increase resilience to seasonal variability

Optimise sowing date, crop species/variety and areas sown

- Use seasonal and long-range weather forecasts to determine rotations and cropping area
 - revise farm plans – do not crop heavy land in dry seasons, cull paddocks early
 - opportunistic cropping when seasons favourable for marginal land
- Account for stored plant available water
- Early/dry sowing
 - sowing into stored soil moisture
 - furrow sowing and water harvesting

Manage crop water use to account for plant available stored water and rainfall

- Manage plant density
 - sowing rate
 - row spacing
- Use seasonal and long-range weather forecasts to manage canopy leaf area index
 - tailor nitrogen fertilisation to season with foliar nitrogen application
 - strategically graze crops to reduce leaf area index and delay flowering

Ensure crop access to nutrients as topsoil dries in spring

- Deeper placement of nutrients at seeding

Manage frost risk

- Use varieties or species that are better able to tolerate frost
- Timing sowing with species and cultivar to minimise frost risk
- Reduce frost risk by managing stubbles
- Site selection – match sowing date and species to topographic location (i.e. frost prone areas may need special management)

Optimise inputs

- Precision farming
 - controlled traffic to maximise fuel efficiency and minimise spray, fertiliser and seeding overlap
 - yield mapping
 - soil testing
 - variable rate seeding, spraying and fertiliser application based on yield potential

Use decision tools

- Use tools such as crop models, flowering calculators and soil water calculators to support decisions about:
 - sowing date
 - variable rate fertiliser application
 - grain marketing
 - evaluate value of soil amelioration
- Input crop imaging data into decision-making tools

Business management

- Change enterprise mix:
 - adjust ratio of cropping to livestock according to terms of trade, land capability and long-term climate trends
 - use dual-purpose crops, such as grazing cereals
 - find new markets for existing agricultural residues, such as straw for biofuel
 - diversify by growing new agricultural products.
- Enterprise size
 - ensure efficiencies of scale
 - reduce local risks by farming over a wider geographical area
- All risk insurance policies
- Ensure there is access to off-farm income
- Undertake ongoing training
- Maintain information and innovation sharing via networks and links

Manage increased soil erosion risk in a drier, more variable climate

- Reduce wind erosion risk
 - reduced tillage
 - stubble retention, such as reduced tillage and stubble burning, livestock management
 - windbreaks on very erosion prone sites
 - claying
- Reduce water erosion risk
 - reduced tillage
 - stubble retention
 - contour farming, including drainage in high rainfall regions
 - claying
 - vegetated buffers along waterways

Appendix D Adaptation options for the broadacre livestock sector

Livestock management

Use livestock breeds or species that are adapted to warmer conditions

- Within-breed selection for heat tolerance such as plain-bodied rather than wrinkly skinned sheep
- Heat-tolerant breeds and crosses such as Brahman cattle and crosses
- Change species such as sheep or goats instead of cattle
- Selection for disease and parasite tolerance

Develop protocols for moving, handling and transporting livestock during hot periods

Ensure livestock have access to cool, clean water and shade during hot periods

Grazing and pasture management

Improve pasture rainfall use efficiency

- Remove physical constraints to root growth
 - drainage to reduce waterlogging, such as deep drains, raised beds, surface drainage
 - deep-ripping to remove hard pans
 - gypsum to improve soil structure
 - controlled traffic farming to reduce compaction
 - increase soil organic carbon content with perennial pastures
- Remove chemical constraints to root growth
 - apply micronutrients and macronutrients
 - liming to increase soil pH
 - drainage to reduce sodicity
- Use pasture varieties/species with increased ability to explore soil profile
 - root morphology (deep vs lateral roots)
 - tolerance of chemical soil constraints, such as pH, boron, aluminium and transient sodicity
 - ability to grow through soil physical constraints such as hard pans or transient waterlogging
- Improve soil water-holding capacity
 - increase soil organic carbon content
 - deep-ripping
 - gypsum to improve soil structure

- controlled traffic farming to reduce compaction
- claying (surface application/delving/spading) to reduce non-wetting
- Root rip along tree lines
- Reduce evaporation from soil by increasing deep infiltration of rainfall
- Reduce run-off

Use best adapted pasture species and varieties

- Use varieties or species with increased drought resistance, such as stay-green varieties
 - physiological tolerance of hot conditions
 - physiological tolerance of dry conditions
 - ability to maintain cell turgor
 - stomatal resistance
- Use varieties or species which are better able to exploit the fertilisation effect of increased atmospheric CO₂ to improve water use efficiency
- Use varieties or species bred to resist current and disease risks and new risks presented by changing climate

Optimise inputs

- Precision farming
 - use remotely sensed data to map productivity
 - soil testing
 - variable rate seeding, spraying and fertiliser application based on yield potential and soil tests

Fodder conservation

- Hay
- Silage

Use grain and graze strategies

- Use dual-purpose crops, such as grazing cereals
- Sow winter crops into summer active perennial forages

Confined feeding

- Feed supplementation, such as summer/autumn feedlots to maintain stocking rates to use greater winter production that will occur with warmer winters

Use decision tools

- Use tools such as forage production models incorporating utilisation rates, seasonal and long-range weather forecasts, remotely sensed production data and

soil water calculators to estimate livestock carrying capacity and feed requirements and assist with decisions about:

- scheduling feed supplementation and forward contracting feed supplies
- forward planning for agistment
- evaluate value of soil amelioration
- Matching stocking rates to projected carrying capacity
- Modify timing of mating and weaning based on seasonal conditions

Livestock water

- Design dams and catchments to cope with current and projected rainfall and evaporation rates
- Treat roaded catchments with chemical sealants to reduce the rainfall run-off threshold to 4–6mm
- Plan for increased investment in tanks and dams storages

Business management

- Use a combination of rotational grazing, supplementary feeding and fodder conservation for livestock to adapt to dry and variable seasons
- Systems facilitating trade cattle through alliances between pastoral and southern broadacre enterprises
- Change enterprise mix
 - adjust ratio of cropping to livestock according to terms of trade, land capability and long-term climate trends
 - diversify by growing new agricultural products
 - Carbon farming
- Enterprise size
 - efficiencies of scale
 - reduce local risks by farming over a wider geographical area
- All risk insurance policies
- Access to off-farm income
- Undertake ongoing training
- Maintain information and innovation sharing networks and links

Manage increased soil erosion risk in a drier more variable climate

- Grazing management to maintain minimum anchored vegetation cover
 - windbreaks on very erosion prone sites
 - claying
 - contour farming, including drainage in high rainfall regions
 - vegetated buffers along waterways

Appendix E Adaptation options for the horticultural sector

Use best adapted crop species and varieties

- Use crop varieties, species or rootstocks with increased physiological tolerance of hot conditions
 - varieties with reduced chill requirements
- Use varieties or species which are better able to exploit the fertilisation effect of increased atmospheric CO₂ to improve water use efficiency
- Change crop rotations and schedules
- Use crop varieties or species bred to resist current and disease risks and new risks presented by changing climate
 - Crop rotation for disease management

Improve water harvesting and storage

- Design dams and catchments to cope with current and projected rainfall and evaporation rates
- Treat roaded catchments with chemical sealants to reduce the rainfall run-off threshold to 4–6mm
- Reduce evaporation loss from dams
 - suspended and floating covers and monolayer films applied to the water surface
 - windbreaks
- If available use treated sewage or grey water for crop irrigation
- In-row water harvesting for grapes and tree crops
- Harvesting water run-off from greenhouses
- Desalination and reverse osmosis to recover otherwise unusable or saline water
- Plan for increased investment in tanks and dams storages

Irrigation efficiency

- Watering at night
- Subsurface drip irrigation
- Improved irrigation scheduling based on monitoring soil water content, soil type, crop factors and evaporation timing and volume of irrigation
- Regulated deficit irrigation
- Partial root zone drying
- Improve water distribution systems
- Reduce evaporation of soil water
 - mulching

- organic
 - plastic
- rapid crop canopy development/closure
- increase speed and depth of infiltration
 - claying
 - application of surfactants
- Reduce run-off
 - appropriate irrigation rates
 - mulches
 - contour sowing
 - minimum tillage
 - claying

Grow crops under shelters or greenhouses

- Provide shade to reduce canopy temperature and evaporation
- Grow crops in greenhouses to increase productivity
 - plastic tunnels
 - plastic structures with computerised temperature control and shading systems
 - glass structures with computerised temperature control and shading systems
 - use hydroponics to increase water use efficiency

Managing higher temperatures

- Chemical dormancy breakers such as application of hydrogen cyanamide as a method to promote budburst
- Crop regulation and canopy management such as the use of temperature data loggers to optimise bunch-zone temperatures
- Use irrigation to ameliorate temperature extremes
 - Sprinkler irrigation can be used to reduce canopy temperatures

Improve plant water use efficiency

Increase plant ability to access soil water

- Remove physical constraints to root growth
 - gypsum to improve soil structure
 - increase soil organic carbon content, such as applying organic mulches and manure
 - deep-ripping to remove hard pans
 - drainage to reduce waterlogging, such as deep drains, raised beds, surface drainage
- Remove chemical constraints to root growth

- application of micronutrients and macronutrients
- liming to reduce pH
- drainage to reduce sodicity
- Use crop varieties, species or rootstocks with increased ability to explore soil profile
 - root morphology (deep versus lateral roots)
 - tolerance of chemical soil constraints, such as pH, boron, aluminium, transient sodicity
 - ability to grow through soil physical constraints, such as hard pan, transient waterlogging

Increase volume of plant available soil water

- Improve soil water-holding capacity
 - increase soil organic carbon content
 - reduced tillage
 - deep-ripping
 - gypsum to improve soil structure
 - claying (surface application/delving/spading) to reduce non-wetting

Use decision support tools

- Use seasonal and long-range weather forecasts to determine rotations and cropping area
- Variable rate seeding, spraying and fertiliser application based on yield potential and soil testing
- Use tools such as crop models, flowering calculators, soil water calculators to support decisions about:
 - sowing date
 - variable rate fertiliser application
 - evaluate value of soil amelioration

Business management

- Change species mix when the cost of water increases to achieve maximum financial return per unit of water
- Relocate production of heat/water sensitive crops to cooler/wetter areas
- Access all risk insurance policies
- Risk management strategies should be in place to manage productivity variability within and between seasons
- Create and sell carbon credits by nitrous oxide emissions from soil, sequestering carbon in the soil or improving energy efficiency

- Improve energy use efficiency
 - improvements in energy efficiency for irrigation
 - reduce post-harvest chilling costs and energy use
 - harvest at night or early morning
 - understanding how quickly and by how much produce temperatures need to be reduced after harvest
 - generate renewable energy on-farm
- Undertake ongoing training in business management
- Maintain information and innovation via sharing networks and links

Manage increased soil erosion risk in a drier, more variable climate

- Reduce wind erosion risk
 - reduced tillage
 - stubble retention
 - windbreaks on very erosion prone sites
 - claying
- Reduce water erosion risk
 - reduced tillage
 - stubble retention
 - contour farming (including drainage in high rainfall regions)
 - claying
- Vegetated buffers along waterways

Public policy

- Identify and protect priority horticultural land
- Moving to water pricing that reflects the true cost of water
- Removal of uncertainty related to water allocation and low water availability, including restricted water allocations to limit irrigation of poor returning crops
- Further reduction of barriers and distortions to water trading
- Optimising the environmental water allocation, and seeking synergies between environmental and irrigation water allocations
- Facilitating water allocation carryover and capacity-sharing at larger scales

Appendix F Adaptation options for the pastoral sector

Livestock management

Use livestock breeds or species adapted to warmer conditions

- Within-breed selection for heat tolerance
- Heat-tolerant breeds such as Brahman cattle and crosses
- Change species, for example, sheep or goats instead of cattle
- Selection for disease and parasite tolerance

Grazing and pasture management

Increase range utilisation

- Increase number and distribution of watering points
- Decrease paddock size to facilitate resting and utilisation

Fodder conservation

- Hay
- Silage

Confined feeding

- Where fresh water resources exist, use irrigation to grow fodder and finish cattle by lot feeding

Use decision tools

- Use tools such as forage production models incorporating utilisation rates, seasonal and long-range weather forecasts, remotely sensed production data and soil water calculators, to estimate livestock carrying capacity and feed requirements and assist with decisions about:
 - scheduling feed supplementation
 - forward contracting feed supplies
 - forward planning for sales or agistment
- Matching stocking rates to projected carrying capacity
- Modify timing of mating and weaning based on seasonal conditions

Livestock water

- Design dams and catchments to cope with current and projected rainfall and evaporation rates
- Treat roaded catchments with chemical sealants to reduce the rainfall run-off threshold to 4–6mm
- Plan for increased investment in tanks and dams storages

Business management

- Systems facilitating trade cattle through alliances between pastoral and southern broadacre enterprises
- Alternative on-lease activities, such as horticulture or tourism
- New income streams from carbon farming activities such as modified savanna burning or carbon sequestration
- Access to off-farm income
- Undertake ongoing training in business management
- Maintain information and innovation sharing networks and links

Manage increased soil erosion risk in a drier more variable climate

- Grazing management to maintain minimum anchored vegetation cover

Appendix G Adaptation options for the intensive livestock sector

Livestock management

Use livestock breeds or species adapted to warmer conditions

- Within-breed selection for heat tolerance
- Selection for disease and parasite tolerance

Modify timing of mating and weaning

- Avoid hot periods and take advantage of greater winter pasture production

Avoid heat stress

- Change feeding frequency and time, such as low energy feed in morning, high energy feed at night
- Provide more watering points (cool water) for dairy cattle
- Provide evaporative cooling
- Provide shade using trees and constructed shelters
- Have an extreme heat management plan (dairy)
 - milk and feed dairy cows before 9am and after 5pm on hot days
 - reduce the distance that dairy cows need to walk to the dairy on hot days
 - spray cows with cool water before milking on hot days
- Plan to avoid heat stress around insemination times or allow for decreased conception rates (dairy)

Pasture/forage production

- Use best adapted species and varieties
 - perennial and annual mixes
- Increase intensity and decrease duration of rotation systems
- Plan for increased growth during winter
 - earlier sowing of pastures, forage and feed crops
 - apply fertiliser earlier
- Plan for increased irrigation during spring and autumn
- Forage conservation
- Increase plant water use efficiency (see Appendix C)
- Increase irrigation efficiency (see Appendix D)
- Increase watering points to maintain feed intake in hot conditions (dairy)

- During hot periods provide cattle with a high quality fibre source that will maintain a stable rumen and still provide energy

Use decision tools

- Use tools such as forage production models incorporating utilisation rates, seasonal and long-range weather forecasts, remotely sensed production data and soil water calculators to estimate livestock carrying capacity and feed requirements and assist with decisions about:
 - scheduling feed supplementation, forward contracting feed supplies
 - evaluate value of soil amelioration
- Energy audits
 - use decision tools such as those available from Dairy Australia
- Farm emissions calculators (Dairy Australia)
- Have an extreme heat management plan (Dairy Australia, Australian Pork)

Infrastructure

- Reduce energy requirements
 - passive or energy-efficient cooling of building
 - more efficient irrigation
 - generate power on-site, for example methane capture from covered ponds or biodigesters or solar or wind power
- Invest in multipurpose infrastructure, such as shading, rainfall capture, fodder storage and livestock handling

Water

- Design dams and catchments to cope with current and projected rainfall and evaporation rates
- Treat roaded catchments with chemical sealants to reduce the rainfall run-off threshold to 4–6mm
- Plan for increased investment in tanks and dams storages
- Re-use effluent and water for wash down and irrigation

Business management

- Use a combination of rotational grazing, supplementary feeding and fodder conservation for livestock to adapt to dry and variable seasons
- Change enterprise mix
 - new markets for existing agricultural residues, such as manures to produce bioenergy or compost

- generate and sell carbon credits into the Emission Reduction Fund or other voluntary markets by reducing emissions or sequestering carbon
- diversify by growing new agricultural products
- Enterprise size
 - efficiencies of scale
- All risk insurance policies
- Access to off-farm income
- Undertake ongoing training
- Maintain information and innovation sharing networks and links

Appendix H Climate research and information provided by various agricultural sector peak bodies

Australian Chicken Meat Federation (chicken.org.au/):

- Life cycle assessment

Australian Egg Corporation (aecl.org/):

- Life cycle assessment

Cattle Heat Load Toolbox (<http://chlt.katestone.com.au/>)

Australian Pork (australianpork.com.au/):

- greenhouse gas emissions calculator
- Carbon farming information
- On-farm biogas production and use
- Life cycle assessment

Australian wool innovations (wool.com/):

- Information about climate variability
- Links to climate analysis tools
- Link to FarmGAS a greenhouse gas emissions calculator

Dairy Australia (dairyaustralia.com.au/):

- Greenhouse gas emissions calculator
- Information about climate change impacts and responses
- Information about how to adapt to climate variability and climate change
- Carbon farming information
- Dealing with heat stress cost–benefit calculator

Grains Research and Development Corporation (grdc.com.au/):

- Links to research reports about various aspects of climate change and variability

Horticulture Innovation Australia (horticulture.com.au/):

- Links to research reports about various aspects of climate change and variability

Meat and Livestock Australia (mla.com.au/Home):

- Information about climate change and variability
- Information about greenhouse gas mitigation
- Carbon farming information

Shortened forms

Shortened form	Full name
ABARE	Australian Bureau of Agricultural and Resource Economics
ABS	Australian Bureau of Statistics
APSiM	Agricultural Production Systems sIMulator Model
BoM	Bureau of Meteorology
°C	degree Celsius
C ₃	metabolic pathway in temperate plant species
C ₄	metabolic pathway in tropical plant species
CCRSPI	Climate Change Research Strategy for Primary Industries
CH ₄	methane
CMIP5	Coupled Model Intercomparison Project Phase 5
CO ₂	carbon dioxide
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DAFWA	Department of Agriculture and Food, Western Australia
FFDI	forest fire danger index
G	gigalitre
GFDI	grassland fire danger index
ha	hectare
IPCC	Intergovernmental Panel on Climate Change
IPCC AR5	IPCC Fifth Assessment Report
kg	kilogram
km	kilometre
m	metre
mm	millimetre
NCCARF	National Climate Change Adaptation Research Facility
NRM	natural resource management
ppm	parts per million
RCP	representative concentration pathways
RD&E	research, development and extension
\$/ML	dollars per megalitre of water
SRES	Special Report on Emissions Scenarios
t/ha	tonnes/hectare
WA	Western Australia

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