Understanding and managing impacts of climate change and variability on vegetable industry productivity and profits

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April 2013

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Funding

This project has been funded by HAL using levy funds from the Australian vegetable industry and matched funds from the Australian Government.

The broad objective of this project was to assess the likely impacts of climate change and variability on the productivity and profitability of Australian vegetable industry in the near and medium term, to identify measures that could be undertaken to minimise any adverse impacts and take advantage of opportunities.

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1 Executive Summary

The Australian vegetable industry has recognised that issues around climate variability and climate change may affect growers and the broader industry. This review was commissioned by the industry in 2013 to provide a comprehensive assessment of the threats and opportunities, and to develop a plan for the future.

The Australian vegetable industry is in a strong position to deal effectively with climate change and vegetable growers have a greater capacity to adapt to change more than most other rural industries.

Climate change credentials of the Australian vegetable industry: How are we doing?

The horticulture and vegetable sectors have a very low rate of greenhouse gas emissions per $ of value produced. The vegetable sector produces 85 t CO_2-e for every $1M in revenue generated and the horticulture industry generally produces 83 t CO_2-e for every $1M in revenue generated (at the farm gate). The total emissions for horticulture are only 1% of agriculture or 0.12% of the national total. Vegetables are even less, at 0.05% of total emissions. These figures are low relative to other rural industries. For example, beef cattle emit 6686 t CO_2-e for every $1M in revenue, and sheep emit 3513 t CO_2-e for every $1M in revenue.

The vegetable industry is, however, characterised by a high level of inputs and this results in a high average greenhouse gas intensity of about 9.2 t CO_2-e per hectare.

Vegetables have a low carbon (and water) footprint compared to most other food items and this is likely to be a significant marketing advantage for the industry into the future. Consumers are becoming more aware of the carbon and water footprints of the food they eat, and may influence the buying decision of consumers, it may in the future.

What will happen to the climate in our vegetable growing regions?

While there is debate in the rural community about the cause(s) of our changing climate, there is no disputing that changes have already occurred. Since 1960 the mean temperature in Australia has increased by about 0.7°C. Some areas have already experienced a warming of 1.5 – 2°C. The strongest warming has occurred in inland regions during spring (about 0.9°C) and the weakest in summer (about 0.4°C). The intensity and frequency of extreme weather events such as floods, cyclones, droughts and heatwaves are projected to increase. Recent extreme climate events have been linked to climate change.

Expected impacts on temperature

Changes in climate observed over the last 50 years will continue. For Australia, our best estimates are that by 2035 the temperature is projected to warm by about 1°C over Australia above 1990 levels. Inland areas are likely to experience stronger warming of up to 1.8°C.

Southern winter production areas such as Werribee, Cranbourne and East Gippsland will benefit from higher average winter temperatures (0.5 – 1.2°C). These areas are used for summer production of leafy vegetables and will also experience higher average summer maximum temperatures (0.6 – 1.3°C), making them more marginal. The northern cool-season production areas such as Stanthorpe and the Atherton Tableland will become more marginal for cool-season crops.

Central and northern regions used for winter and transition-period production of cool-season crops will become more marginal at the boundaries of the seasons (early and late). Examples of these areas are the Lockyer Valley in spring/autumn for leafy vegetables and brassicas, central highlands and mid western areas of NSW.

Warm-season crops in summer production areas will be less affected. There will be some effects on crops such as tomatoes and capsicums where pollination is adversely affected by average temperatures above 27°C, and there will be a marginal reduction in the length of production seasons.

The seasonality of frosts has already changed over the last 20 years, and analyses have revealed that in eastern Australia, the frost window is both starting earlier (on average up to 10 days earlier by 2010) and ending later (up to 46 days later by 2010). The change in the frost window is consistent with climate change projections.

Expected impacts on rainfall and water

Rainfall patterns will become more variable, but total rainfall amounts are not expected to change significantly, with exceptions such as south-western WA where rainfall is projected to continue to decline.

Rainfall is projected to decrease by 2-5% on average by 2035 (compared to 1990). The rainfall in far northern Australia is not expected to change. The rainfall in south-western Australia is projected to decline by 5-9% by 2035 adding to a 15% decline since 1988.

Crop water use is not predicted to change significantly and it is likely that the largest impact on crop water use will be the availability of water for irrigation, particularly where water sources are localisled, eg Lockyer Valley; Munjimup; Werribee.

Climate threats and opportunities

The main climate-related threats in the short and medium terms will be:

- Short term: (1-5 years) effects are increased weather variability and frequency of extreme weather events in our vegetable growing areas. This is already occurring.
- Longer-term: (20 years) effects are increases in average temperature from 1-1.8^{o}C, increased variability and a longer frost window resulting in higher risk of frost damage.
- Extreme events: If cropping systems already struggle with weather extremes, which historically may only have occurred 1 or 2 years in 10, these events will become the average by 2035.
- Pests and diseases: There may also be new challenges arising from a sustained increase in winter minimums. For example, pest and diseases that were previously unable to overwinter may now become problematic more often and earlier in the season.

Strategies for the future

Project outputs and material relevant to the vegetable industry is now available on the Vegetable Climate website (www.vegetableclimate.com), which is the place to go for all the project outputs, resource material and current information on climate variability and the Australian vegetable industry. It covers:

- **Climate Variability**: Current assessment; Predicted changes; Regional predictions.
- **Government Impacts**: Policy and regulations; Carbon Farming Initiative; Government support & funding.
- **Vegetable Industry Impacts**: Climate credentials; Crop impacts; Profitability; Research and reports.
- **Strategies**: Energy efficiency; Adaptation; Mitigation; Tools.

The most promising immediate actions that Australian vegetable growers can take to minimise the impacts of climate policies and increased climate variability, and prepare for the future are:

Improve electricity use efficiency: Electricity for running pumps and cool rooms is a major cost for the Australian vegetable industry and savings in both cost and emissions can be achieved now through improving the efficiency in the way energy is used by vegetable farms. There are three ways in which this can be achieved:

- Reducing electricity use for irrigation: Improvements in energy productivity or reductions in energy usage in relation to irrigation.
- Electricity use for cooling: improvements in refrigerants and refrigeration plant, refrigerants and revised produce-cooling protocols.
- On-farm power generation technologies and related options.

Adaptations: There exists a range of adaptations to climate change and increased variability that can be used right now. They include:

- Breeding or selecting varieties that will grow in the changed climate.
- Adapting planting times or production slots in regions.
- Protected cropping including shade.
- Use of irrigation to manage frost and high temperature spikes.
- Irrigation for increased water-use efficiency and profitability when water is scarce.
- More efficient postharvest cooling and temperature management.

Reducing on-farm emissions (mitigation): The main source of direct greenhouse gas emissions from vegetable farms are nitrous oxide emissions from soils. These can be reduced through better management of nitrogen, or potentially through the use of nitrification inhibitors. Carbon can be stored in soils as biochar.

Funding: There is funding available for assistance with implementing energy efficiencies and undertaking activities related to the CFI.

For the longer term: In the longer term some key areas of focus for increasing our capacity for a viable vegetable industry include:

- Improved medium-range weather forecasting (3 months).
- Better forecasting of extreme events.
- Understanding pest and disease interactions in a changing climate.
- Varieties which can produce good quality and high yields in a more variable climate.
- Region-specific information on how crops will perform in our vegetable growing areas.
- Innovative energy-efficient protected cropping for vegetables.
- Improved on-farm power generation and more efficient cooling.

2 Introduction

The Australian vegetable industry has recognised that issues around climate variability and climate change may affect growers and the broader industry. As a result, this review was commissioned in 2013 to provide a comprehensive assessment of the threats and opportunities, and to develop a plan for the future.

The Australian vegetable industry is in a strong position to deal effectively with climate change. The industry has excellent climate change credentials, is a low emitter of greenhouse gasses on a productivity basis, and has one of the lowest carbon and water footprints of any food producer. Vegetable growers also have greater capacity to adapt to change than most other rural industries.

The threats, however, are serious, and the industry should not be complacent. The viability of vegetable production can be affected either by the physical impacts of a changing climate, or by government policies aimed at addressing climate issues. This review has focussed on identifying actions growers and the industry can take in the short and longer term to safeguard the Australian vegetable industry against climate-related threats.

Industry and farm managers will need to distinguish between 'old climate expectations' and 'new climate realities[1]' in determining how best to adapt vegetable farming to our more variable climate and where possible, further reduce our greenhouse gas emissions.

The project team has produced detailed summaries and analyses of likely regional impacts on the production, marketing and distribution of major vegetable crops, impacts of government policy, strategies for dealing with change, and opportunities for funding to support these measures. There is also a research investment plan to help inform the future direction of investment in climate change by the vegetable industry.

The *Vegetable Climate* website has been developed, and is the place to go for all the project outputs, resource material and current information on climate variability and the Australian vegetable industry.

The challenge for the industry is to develop a clear strategy for how best to adapt to anticipated climatic and atmospheric changes, in ways that minimise adverse financial and environmental impacts and take best advantage of any positive changes. This review will build on previous climate change studies conducted for the horticulture industry.

[1] P. Deuter, 'Scoping Study: Climate Change and Climate Variability - Risks and Opportunities for Horticulture: VG05051', Horticulture Australia, 2006

How is the climate predicted to change in the short and medium term?

2.1 Climate change and variability – what has already occurred?

While there is debate in the rural community about the *cause(s)* of our changing climate, there is no serious dispute that changes have already occurred (Australian Bureau of Meteorology):

- Since 1950 the global average surface temperature has risen 0.7°C and 0.9°C in Australia.
- The climate is now more variable.
- There are fewer cold days and cold nights and more hot days, hot nights and heatwaves.
- Heavy rainfall events have increased in frequency.
- Rainfall has increased over northwest Australia while eastern and south-western Australia have become drier.

These changes suggest a need for growers to alter their practices to minimise the risks and impacts presented by the changing climate, and to take full advantage of any opportunities these changes might bring.

Global atmospheric CO_2 levels have risen since pre-industrial times from 280 parts per million (ppm) to a current (2013) level of 396 ppm. This higher level of atmospeheric CO_2 has direct effects on plant growth, which for the vegetable industry may be beneficial. The three main direct impacts of higher CO_2 on vegetable crops are:

- Faster growth rate due to more efficient photosynthesis.
- Improved water-use efficiency.
- Improved nitrogen-use efficiency.

The challenge for the Australian vegetable industry is to develop a clear strategy for how to adapt to these climatic and atmospheric changes, in a way that minimises adverse financial and environmental impacts and takes best advantage of any positive changes.

2.1.1 ***Risk analysis of climate change from a broad perspective***

For the third year running climate change was the standout risk for Australia in KPMG's yearly report (KPMG 2012) on risks and opportunities (Figure 1).

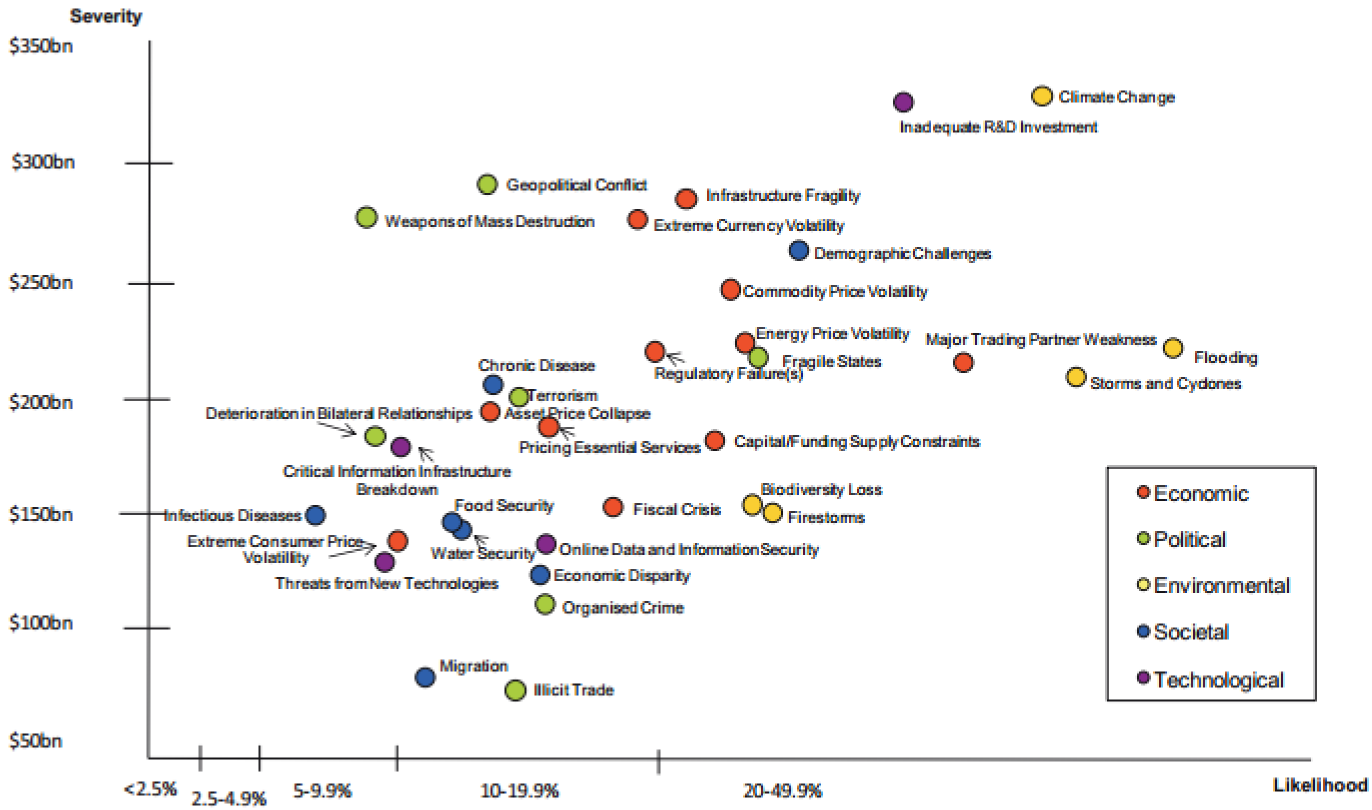

Figure 1. The Australian risk landscape, as per responses of Australian business, government and academia leaders to a survey on the likelihood and impact to the Australian economy of 34 key risk areas across the categories of economic, political, environmental, societal and technological[2].

Climate change topped both the severity and likelihood rankings. The linkages to storms and cyclones, firestorms, flooding, biodiversity loss, food and water security, infectious diseases and infrastructure fragility were also highlighted.

The short- to medium-term responses to climate change by government, businesses and communities outlined in the following questions aims to manage the potential risks associated with climate change.

Deciding on an appropriate response means dealing with uncertainties. Climate change uncertainty can broadly be summarised as resulting from either the science:

[2] KPMG (2012). Australia Report 2012 – Risks and Opportunities. Australia, Report prepared by ADC in collaboration with KPMG.

- How much will the climate warm for a given amount of greenhouse gases in the atmosphere (climate sensitivity)? This aspect of uncertainty is at the core of debates on anthropogenic causes of climate change.
- Where, when and how will the climate change?
- How much additional warming could occur due to amplifying effect (positive feedbacks) such as large-scale changes? There is the potential for additional greenhouse gases to be released as the climate changes. For example, in Australia forests or woodlands may change to grassland if temperature and rainfall changes increase fire intensity and frequency. In the Arctic methane release from the frozen soils could have a large impact.

or how we respond:

- What global action will occur to reduce future greenhouse gas emissions?
- What government policy responses will occur?
- How will businesses and communities respond to policy, voluntary markets and trade mechanisms to reduce emissions?
- What will be the timing and scale of mitigation actions?

Uncertainty and risk are quintessential features of the vegetable industry due to seasonal production and price uncertainties. Climate change introduces more uncertainty into the strategic time horizons. Where should I buy land? Should I invest in a processing plant? How reliable will my water entitlement be? Should I be changing cropping systems? These are strategic decisions which could be affected by changes to the climate.

2.1.2 What we know about the atmosphere and climate

Greenhouse gases in the atmosphere have changed – very quickly and to levels not usually seen. Global carbon dioxide concentrations have risen rapidly over the last century (Figure 2). Methane, another greenhouse gas, has shown similar increases. The carbon dioxide concentration in 2013 of 396 parts per million (ppm) is much higher than the natural range of 170-300 ppm that has existed in the atmosphere for at least the past 800,000 years and possibly the past 20 million years.

The changes in greenhouse gases in the atmosphere are linked to changes in the global climate. Over the past 50 years Australia's climate has changed[3]. Since 1960 the mean temperature in Australia has increased by about 0.7 °C. The long-term trend in temperature is clear, but there is still substantial year-to-year variability of about ±0.5 °C. Some areas have experienced a warming of 1.5 to 2 °C over the last 50 years. Warming has occurred in all seasons, but the strongest warming has occurred in spring (about 0.9 °C) and the weakest in summer (about 0.4 °C).

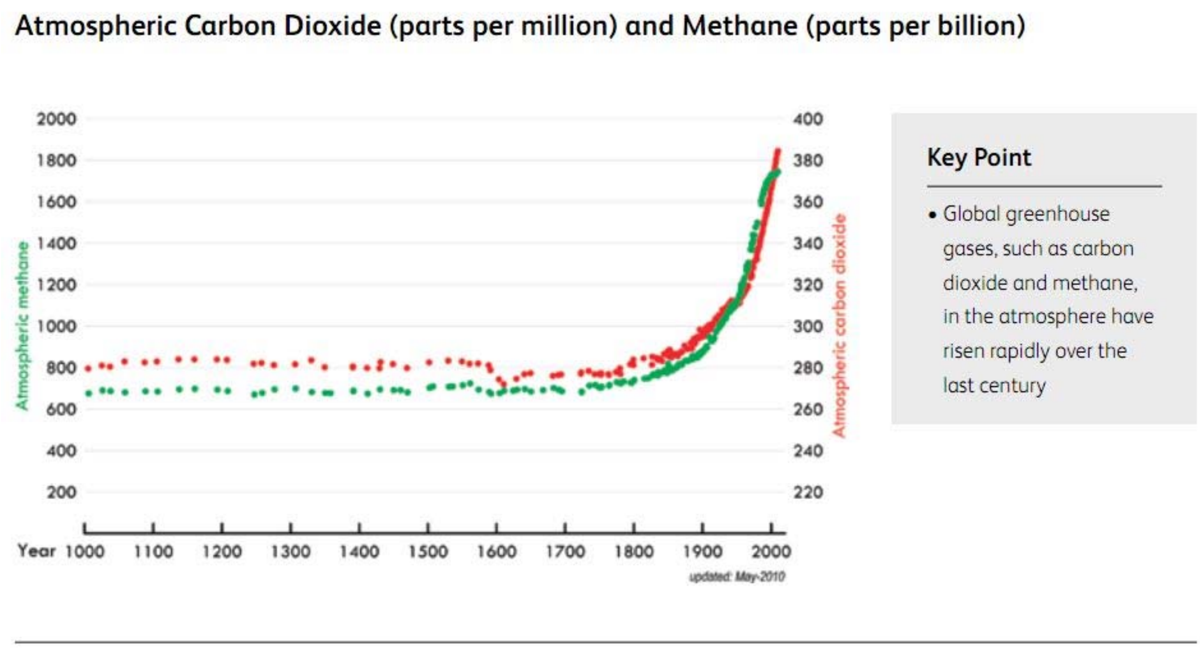

Figure 2 Atmospheric carbon dioxide and methane(CSIRO 2010)

3 CSIRO (2010). State of the Climate. . Canberra, Bureau of Meteorology and CSIRO.

2.1.3 What could happen to the climate?

What could happen to the climate in the next 50 years and beyond will depend on both how mankind and the climate system responds. Models manage this uncertainty by producing a range of climate projections to take account of different scenarios, with their associated greenhouse emission projections.

The changes in climate observed over the last 50 years are projected to continue. For Australia, our best estimates are that by 2035, the temperature is projected to warm by about 1°C over Australia for the mid-range emissions scenario (NB based on current emissions we will exceed the high growth scenario used by models). Inland areas are likely to experience stronger warming of up to 1.8 °C.

By 2070, average Australian temperatures are projected to increase by about 1.8 °C in a low emissions scenario, with a range of 1.0-2.5 °C across the country. In a high emissions case the projected average temperature increase is about 3.4 °C, with a range of 2.2-5.0 °C, relative to 1990.

In south-eastern Australia, El Niño events may tend to become drier and La Niña events may become wetter[4]. For 2035, rainfall is projected to decrease by 2-5% on average, and by about 7.5% by 2070 (compared to 1990). The exception is far northern Australia where little rainfall change is projected. However, changes in rainfall are expected to vary widely across regions and seasons. For example, rainfall in south-western Australia is projected to decline by as much as 40% by 2070.

These changes will impact on investments and natural resource decisions made this decade – for example, investment in irrigation infrastructure, biodiversity plantings and water management – and will have implications for the next 20-30 years.

2.1.4 Will there be more extreme weather events?

Discussions about a 2°C rise in average temperature as a result of increasing concentrations of greenhouse gasses in the atmosphere tend to understate the likely impacts we will see as a result of this change. These likely impacts are increased intensity and frequency of extreme weather events such as floods, cyclones, droughts and heatwaves. These events, together with the predicted rise in seas levels, will have a far more significant impact on vegetable production than would a 2°C increase in average temperature alone.

[4] CSIRO (2007). Climate change in Australia – observed changes and projections Canberra, CSIRO and Bureau of Meteorology.

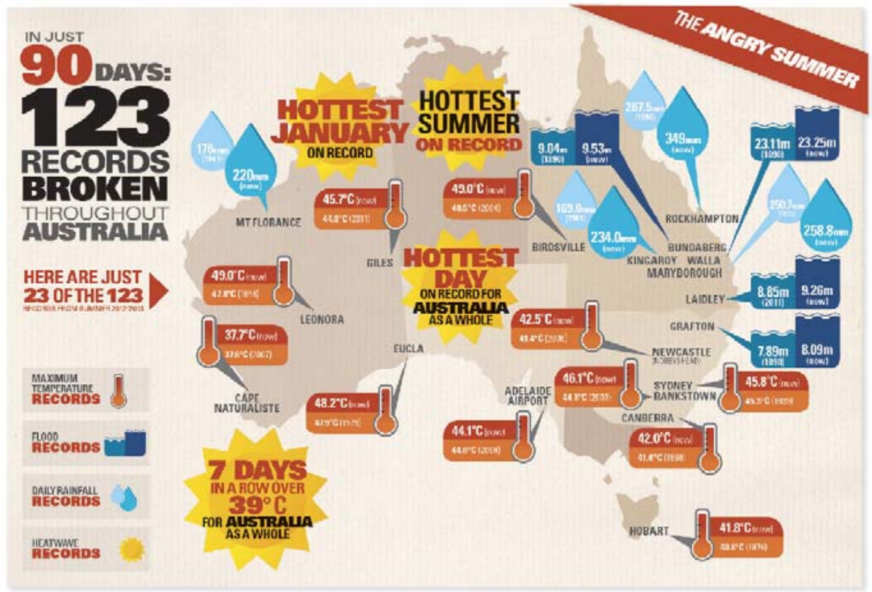

Figure 3 The Angry summer: Climate Commission 2013

In recent years we have been experiencing extreme weather events on a regular basis, which have major impacts on the Australian vegetable production industry. A recent climate commission report "The Angry Summer" lists 123 climate records which were broken in just 90 days in the 1012/13 summer (Figure 3)[5]. Specific examples include:

- ***Heatwaves*** across much of eastern Australia in January 2013, including hottest day ever in Sydney (46^{o}C) on 18th January. Temperatures regularly above 48°C, with the highest recorded maximum of 49.6°C at Moomba in South Australia. The extreme conditions have been associated with a delayed onset of the Australian monsoon, and slow moving weather systems over the continent (The Conversation: 18th January 2013). Australia in 2013 has recorded its hottest summer on record with an average summer temperature of 28.6^{o}C.
- ***Severe flooding*** in Queensland and NSW in January/February 2013 and 2012 including extreme events in Toowoomba, the Lockyer Valley and Brisbane (2012) and Bundaberg (2013).
- ***Drought***: Australia was gripped by a severe drought from 2003 to late 2010 caused by an extended El Nino event that necessitated water restrictions across the country and strict irrigation restrictions in all vegetable-growing regions, with the exception of the Ord River.
- ***Cyclones***: Recent category 5 cyclones have caused serious damage to cropping in Northern Australia, e.g. cyclone Yasi (January 2011) and cyclone Larry (March 2006).

While it can be difficult to attribute individual extreme events to a changing global climate, examining extreme incidents collectively on a global scale and comparing them to historical averages, significantly increases the certainly with which judgements can be made. To

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[5] The Angry Summer, Climate commission report 2013.

address this issue, the IPCC has conducted a study recently on the effect of climate change on the occurrence of extreme weather events, and produced a report on the risks of extreme weather events: *Managing the risks of extreme events and disasters to advance climate change adaptation: Special report of the intergovernmental panel on climate change*[6]. This detailed report (592 pages) has examined the available data and has described likelihoods of a range of extreme events occurring. A summary of the findings from that study are outlined below:

Temperature

- It is *virtually certain* that increases in the frequency and magnitude of warm daily temperature extremes and decreases in cold extremes will occur in the 21st century at the global scale.
- It is *very likely* that the length, frequency, and/or intensity of warm spells or heat waves will increase over most land areas.
- A 1-in-20 year hottest day is *likely* to become a 1-in-2 year event by the end of the 21st century in most regions, except in the high latitudes of the Northern Hemisphere.

Rainfall

- It is *likely* that the frequency of heavy precipitation or the proportion of total rainfall from heavy falls will increase in the 21st century over many areas of the globe. Heavy rainfalls associated with tropical cyclones are *likely* to increase with continued warming.
- There is *medium confidence* that, in some regions, increases in heavy precipitation will occur despite projected decreases in total precipitation in those regions.
- A 1-in-20 year annual maximum daily precipitation amount is *likely* to become a 1-in-5 to 1-in-15 year event by the end of the 21st century.

Cyclones

- Average tropical cyclone maximum wind speed is *likely* to increase.
- It is *likely* that the global frequency of tropical cyclones will either decrease or remain essentially unchanged.
- There is *medium confidence* that there will be a reduction in the number of extratropical cyclones averaged over each hemisphere.

Drought

- There is *low confidence* that droughts will intensify in the 21st century in some seasons and areas, due to reduced precipitation and/or increased

[6] Field, C. B., V. Barros, et al. (2012). Managing the risks of extreme events and disasters to advance climate change adaptation. Special report of the Intergovernmental Panel on Climate Change.

evapotranspiration in Australia. A lack of observational data, and the inability of models to include all the factors that influence droughts, preclude stronger confidence than *medium* in drought projections.

Flooding

- There is *low confidence* in projections of changes in river floods because there is not enough data, *limited evidence* and because the causes of regional changes are complex.
- There is *medium confidence* (based on physical reasoning) that projected increases in heavy rainfall would contribute to increases in local flooding in some catchments or regions.

Heat waves

- There is *high confidence* that changes in heat waves, glacial retreat, and/or permafrost degradation will affect high mountain phenomena such as slope instabilities, movements of mass, and glacial lake outburst floods.
- There is *high confidence* that changes in heavy precipitation will affect landslides in some regions.

Sea level rise

- It is *very likely* that mean sea level rise will contribute to upward trends in extreme coastal high-water levels in the future.
- There is *high confidence* that locations currently experiencing adverse impacts such as coastal erosion and inundation will continue to do so in the future due to increasing sea levels, all other contributing factors being equal.
- The *very likely* contribution of mean sea level rise to increased extreme coastal high-water levels, coupled with the *likely* increase in tropical cyclone maximum wind speed, is a specific issue for tropical small island states.

2.1.5 Will variability in the weather increase, and if so in what way?

The most significant issue by far will be the predicted increase in the variability of the climate, especially temperature. The figures presented in section 2.7 give an indication of where the variability will occur for the regions studied, and at what time of year. Briefly, these are expected to be:

Gatton, Qld: the most variable times for this region are for minimum temperatures in midwinter and for maximum temperatures in spring and summer.

Hay, NSW: the greatest variability in this region will be in maximum temperatures in spring, summer and autumn.

Werribee, Vic: the greatest variability will be in minimum temperatures throughout the year and maximum temperatures in spring and summer.

Murray Bridge, SA: the greatest variability will be in minimum temperatures in summer, autumn and winter, and maximum temperatures in summer.

Manjimup, WA: the greatest variability in this region will be the spring and summer maximum temperatures.

Devonport, Tas: the greatest variability will be minimum temperatures in summer and autumn.

The science in relation to modelling for extreme weather events and variability is not well developed. This means it is not currently possible to predict with any confidence what the precise variability in temperature will be for Australia's vegetable growing areas[7]. Frustratingly, it is temperature variability, especially high and low temperature spikes, which is precisely the type of information that vegetable growers need for planning in the short and longer term.

We suggest more precise prediction of temperature extremes is a research need for the vegetable industry in Australia: How to model the frequency and magnitude of extreme temperature events in the Australian environment.

The following regional snapshots (Table 1) shows how general projections of broad-scale trends in climate are most likely to play out as changes in particular parts of the continent in 2035 using an assumption of a mid level of emissions, and in 2070 using high and low emissions estimates. The examples of potential impacts that may affect these regions have been drawn from various studies.

Table 1. Average number of days above 35°C

Region	Present average (1971–2000)	2035 average (mid emissions)	2070 average (low emissions)	2070 average (high emissions)
Sydney	3.5	4.4	5.3	8.2
Melbourne	9.1	11.4	14	20
Brisbane	1.0	2.0	3.0	7.6
Adelaide	17	23	26	36
Perth	28	35	41	54
Cairns	3.8	6.6	12	44
Hobart	1.4	1.7	1.8	2.4

Source: (CSIRO)[8]

7 Snow Barlow, pers comm

8 Whetton, P. (2011). Future Australian climate scenarios. Climate change : science and solutions for Australia. H. Cleugh, M. Stafford Smith, M. Battaglia and P. Graham, CSIRO.

2.2 What would 4 degrees of global warming look like?

The CSIRO and the Bureau of Meteorology have considered what a $4^{o}C$ increase in average global temperature would look like for Australia. While targets are being set to achieve a maximum of $2^{o}C$ of global warming by 2100, unless significant changes in greenhouse gas emissions can be achieved, climate models are predicting global warming of $4^{o}C$ or more by 2100[9].

What would $4^{o}C$ of global warming look like? CSIRO has sought to demonstrate the effect of predicted changes by showing what regions would be like in 2100. For example, a $4^{o}C$ rise in average temperature would make the climate of ***Sydney*** like the current climate of ***Brisbane***[10].

Localities in eastern Australia would generally adopt the current climates of regions well to the north (e.g. Sydney -> Brisbane) and coastal regions would tend to adopt climates more like those of the drier interior. In wheat belt towns, such as Dubbo, the climate would become like the arid interior.

The results are striking:

- Melbourne becomes like West Wyalong and Gawler
- Sydney becomes like Brisbane and Hervey Bay
- Dubbo becomes like Charleville and Emerald
- Brisbane becomes like Ayr and Mareeba
- Cairns becomes like Weipa

The figures that relate to these predictions are shown in Appendix 11.6

[9] Climate Change in Australia CSIRO & BoM (2007)
[10] Australian climate at four degrees or more of global warming Penny Whetton (CSIRO) and David Karoly (Uni of Melbourne)

2.3 Climate variability

Regional climates can vary greatly from year to year. The consequent impacts on vegetable growers can be considerable, be it floods in the Lockyer Valley, early frosts in Hay or a prolonged winter drought in Manjimup. This short-term variability is the result of regional atmospheric circulation features summarised in Figure 4[11]. Best know is the El Niño. But El Niño belongs to a growing family of circulation features that are responsible for much of the climate variability in the short term.

Understanding how these features operate and influence the weather in the different regions is progressing rapidly. Increasingly, rain-fed agriculture is using this new knowledge to assist in decision-making. There is the potential for vegetable growers to also benefit from improved understanding of the drivers of climate variability. But as Figure 4 highlights, it is complicated. To help assess the implications for growers, the Managing Climate Variability program has been developed.

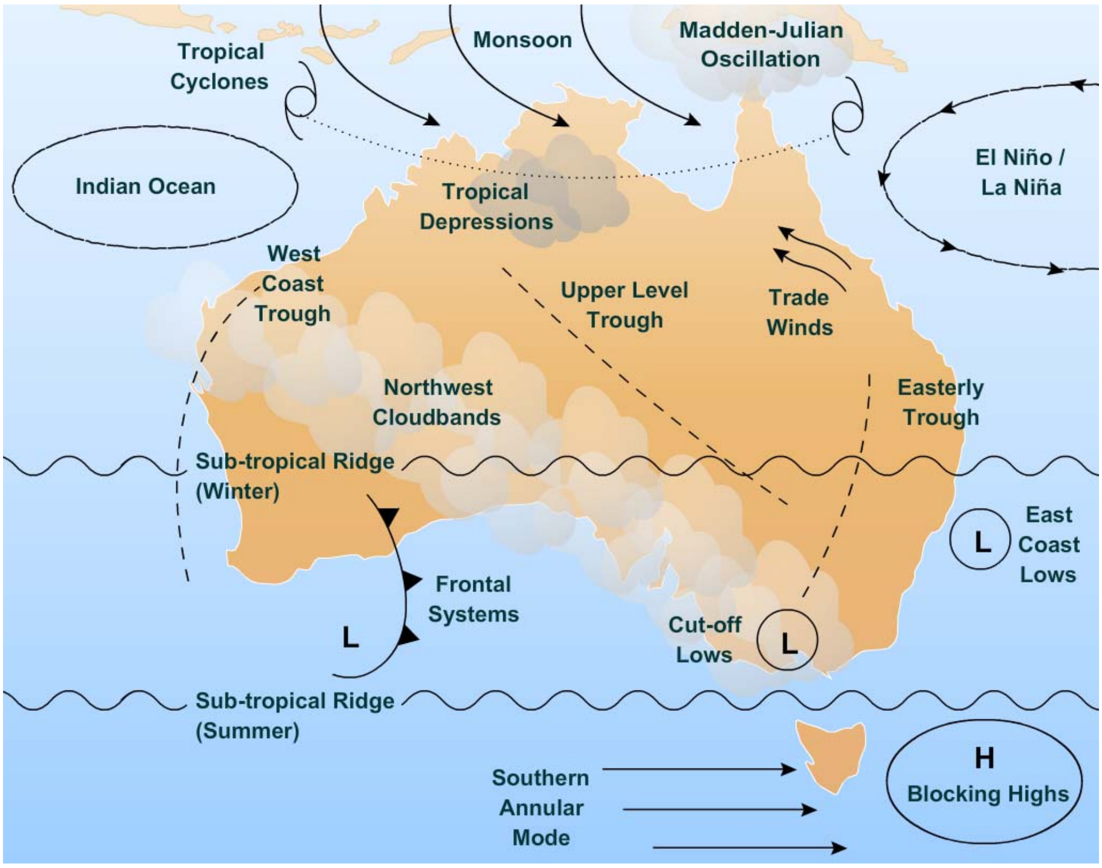

Figure 4. A summary of the family of circulation features that are responsible for much of the climate variability in the short term. (Sources: Climate Change in Australia CSIRO & BoM 2007)

It is through these circulation features that the longer-term climate change plays out. For example, the autumn-winter rainfall declines in south-west WA, and more recently in

[11] Bureau of Meterology, Commonwealth of Australia, http://www.bom.gov.au/watl/about-weather-and-climate/australian-climate-influences.shtml?bookmark=introduction. Accessed 19/3/2013.

Victoria, have been associated with changes in the sub-tropical ridges, the latitude of the mid-latitude storm track and the phase of the southern annular mode, and it is to be expected that they are all inter-related and forced by the same mechanisms[12]. These changes are consistent with those predicted by anthropogenic-force climate change.

Excellent short videos of the key circulation features that explain the drivers of climate variability can be found at "The Climatedogs"[13]. A more detailed explanation of these drivers can be found in Appendix 11.7.

2.4 What are the predicted impacts at the industry level?

The overall impact on the vegetable industry will depend on the region and crops affected. In general the average temperatures will become slightly warmer. For cooler regions, where the average daily temperature is less than 25°C during the growing season, the effects should be positive on yield and quality. This will be a benefit for winter production but make the regions more marginal for summer and transition season production. In warmer regions (average temperature >25^{o}C) the impacts will more likely be negative.

In Australia, these changes mean that southern winter and transition production areas such as Werribee, Cranbourne and East Gippsland, Tasmania will benefit from slightly higher winter temperatures. The southern areas used for summer production of leafy vegetables including southern Victoria will suffer from higher average temperatures, making them more marginal. The northern cool season production areas such as Stanthorpe and the Atherton tableland will also become more marginal for cool season crops.

Central and northern regions used for winter and transition period production of cool season crops will become more marginal at the boundaries of the seasons (early and late). Examples of these areas are the Lockyer Valley in spring/autumn for leafy vegetables and brassicas, central highlands and mid western areas of NSW.

Warm season crops in summer production areas will be less affected. There will be some effects on crops such as tomatoes and capsicums where pollination is adversely affected by average temperatures above 27^{o}C, and there will be a marginal reduction in the length of production seasons, e.g. tomatoes in Bowen.

2.5 Regional risk assessments: Overview

This section is about the risk assessment of climate change. It looks ahead 20 years and asks what sort of climate could you reasonably expect in your region, and what could be the

[12] Bradley Murphy & Bertrand Timbal 2008. A review of recent climate variability and climate change in southeastern Australia. International Journal of Climatology 28: 859–879.
[13] "The Climatedogs" http://www.dpi.vic.gov.au/agriculture/farming-management/weather-climate/understanding-weather-and-climate/climatedogs.

consequences for long-term investment decisions such as property purchase or major on-farm upgrades or changes.

The following regions have been selected for consideration because they are representative of the main vegetable production regions for levy-paying growers:

- Manjimup, WA.
- Gatton, Qld.
- Hay, NSW.
- Werribee, Vic.
- Murray Bridge, SA.
- Devonport, Tas.

For each of the six regions the following two distinct steps have been undertaken:

1. Understanding the projected magnitude and likelihood of changes to key climate variables in a region.
2. Exploring the consequence of the projected changes in climate on the vegetable growing region.

A "discussion starter" is provided on the consequences of these predicted changes on the vegetable producing regions. This recognises that the best people to consider the possible impacts on their region and their businesses are the growers themselves.

2.5.1 Understanding the likelihood of changes to key climate variables in a region

For the six vegetable growing regions, projections for 2035 of mean monthly maximum and minimum temperatures and rainfall were obtained from global climate models using OzClim[14]. OzClim provides an interface for the climate projections from 27 global climate models produced for the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (2007). The projections explicitly account for the key science and policy/behavioural uncertainties outlined below.

2.5.1.1 Scientific uncertainties

The science uncertainties are accounted for by using projections for 2035 from three global models that cover the range of climate projections. Specifically, the different models have differing climate sensitivities (i.e. the amount of warming for a doubling of atmospheric CO_2). The three models used were NASA/GISS: GISS-AOM, CSIRO Mk3.5 and CCR: MICRO-M. These models were chosen because they produced monthly means for temperature and

[14] A Web Based Version of OzClim for Exploring Climate Change Impacts and Risks in the Australian Region
Ricketts, J.H. and C.M. Page

rainfall and covered the range of changes in climate, from high to low. A summary of the models is provided in Appendix 11.2.

Global climate models produce coarse resolution projections. The “down-scaling” process introduces another source of uncertainty. The regional projections used in this report used the same approach[15] and thus do not capture this source of uncertainty. The projections obtained from OzClim have a single value for each grid cell of approximately 25km x 25km. This is a major limitation. Vegetable growing areas are typically localised and may take advantage of microclimate effects. These will not be represented in the regional projections.

2.5.1.2 Policy and behavioural uncertainties

A large source of climate projection uncertainty arises from how the global community might behave in the future and the subsequent impact on global greenhouse emissions. To account for these uncertainties the IPCC developed a series of scenarios or storylines in 2000. These scenarios, and their associated greenhouse gas emission profiles, are used in climate projections by global climate models. A summary of the scenarios is provided as an Appendix 11.3.

This project uses the A2 scenario to capture the policy and behaviour of the globe with respect to emissions out to 2035. This was near the top end of global emissions scenarios when developed in 2000. There is now actual emission data from 2000-2011 on which to evaluate the global community’s behaviour (Figure 5).

The actual global emissions for this period track or exceed the A2 scenario. A noticeable decrease in global emissions was observed during the Global Financial Crisis, but emissions have subsequently recovered and are again tracking above the A2 scenario. Thus the A2 scenario, whilst being at the upper end of global emissions, could still be considered conservative.

Significant worldwide action to reduce global emissions will be required to reduce emissions below these levels. Within the timeframe of these projections, out to 2035, it is unlikely that reduction in global emissions will be large enough to substantially change the projections used in this report.

[15] Australian climate change projections for impact assessment and policy application: A review P. H. Whetton, K. L. McInnes, R. N. Jones, K. J. Hennessy, R. Suppiah, C. M. Page, J. Bathols and P. J. Durack. CSIRO Marine and Atmospheric Research Paper 001, December 2005.

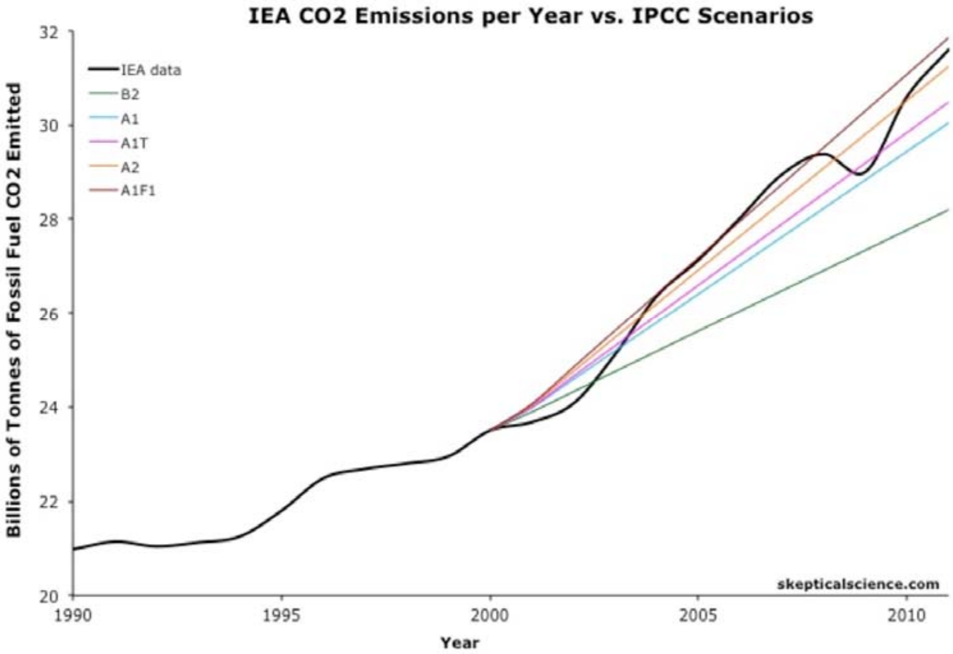

Figure 5. Global CO_2 emissions consistently tracking above the IPCC A2 scenario[16].[17]

2.5.2 How good have past climate change projections been?

Climate change projection has been around for a few decades now, which allows us to look at how the projections stack up against actual weather.

What were the projections for WA?

In 1988 climate change projections for Western Australia were presented by the Bureau of Meteorology at the Greenhouse 88 Conference[18].

The 1988 climate change projections described the most likely scenario at 2040 and included:

- Southward shift in winter rainfall systems.
- Increased sea surface temperatures and southward occurrence of tropical cyclones.
- Decreased winter (JJA) rain of between 10% and 20%.
- Increased summer rain for Kimberley and Pilbara (50%).
- Increased summer rain over the Wheatbelt and Goldfields (40%).

[16]from J Cook, 29 May 2012.IEA reveals emissions are up again, but it's not all bad news, The Conversation http://theconversation.edu.au/iea-reveals-emissions-are-up-again-but-its-not-all-bad-news-7321

[17] The International Energy Agency (IEA) is an autonomous organisation which works to ensure reliable affordable and clean energy for its 28 member countries (www.iea.org).

[18] Ian Foster 2013. Assessment of climate change projections for WA – new tools for adaptation. 2013 Crop Updates Conference, Burswood, 26 February 2013.

- Winter temperature rise by 1.8 to 2.1 ºC (summer up by 1.2 – 1.5 ºC).

What has been observed?

At the half-way mark the projections have predicted the direction of change accurately (Table 2). Some of the specific projections have underestimated the change, e.g. the decline in winter rainfall has been greater than expected, while some have overestimated the change, e.g. the amount of warming has not been as strong as projected. However, this may be due to the simple linear adjustment of 2040 projections to 2012, as changes to the climate are typically non-linear.

Table 2. Comparison of South Western WA 2040 climate projections, linearly adjusted to 2012, with actual changes from 1988-2012.

	Winter	Summer
Rainfall		
Projected 2040	-10 to 20%	Up to + 40%
Projected – adjusted to 2012	-6% to -9%	+19%
Actual (1988-2012)	-15%	+6%
Temperature		
Projected 2040	+1.8 to 2.1ºC	+1.2 to 1.5ºC
Projected – adjusted to 2012	+0.3 to +0.4^{o}C	+0.2 to +0.3^{o}C
Actual (1988-2012)	+0.14 deg C	+0.03 deg C mixed pattern

Climate projections for WA, made from as early as 1988, have provided a consistent indication of likely changes to our climate. Weather patterns have changed as expected, but the South West has dried faster than projected. This gives some confidence that the projections for 2035 are realistic.

2.5.3 Exploring the consequence of the projected changes in climate on the vegetable growing region – "Discussion Starters".

For each region, the consequence for the vegetable industry of the projected changes to the climate are considered, using the following framework:

Growing conditions - impact of changes to maximum and minimum temperatures and frost incidence on crop establishment, growth and maturity. These include extremes (hot and cold) and prolonged heatwaves.

Water – possible changes to irrigation demand, local and regional water supply, and flooding incidence.

A useful way of thinking about what the 2035 climate might be like for growing vegetables is to consider how your current production system has coped with the recent extremes. For example, if your cropping system struggled with the warmer temperatures, which historically may only have occurred 1 or 2 years in 10, and which for 2035 is now the average climate, this highlights a potential risk to the region and your production system.

There may also be new challenges arising from a sustained increase in winter minimums. For example, pest and diseases that were previously unable to overwinter may now become problematic more often and earlier in the season.

Wine industry example: **"Treasury hunts for cooler vineyards as climate shifts"**

The wine industry is already on the lookout for cooler climates. *Treasury Wine Estates*, the world's second-largest listed wine company, is seeking out vineyards in cooler regions in preference to ones in warmer areas as climate change starts to shift growing seasons.

"As the world heats, Tasmania's very well positioned because of the cooler climate. We've got out of places like the Hunter; in the longer term I think it will be hot and dry and expensive," Chief Executive Officer David Dearie said. (source: Sydney Morning Herald, April 12, 2013).

2.6 Regional risk assessments: Interpretation

In this section the climate projections for 2035 are compared with the actual climate (1961-1990) for the six regions. Before looking at individual regions there are some factors to consider which are common across all regions. These are outlined below to assist in understanding what the regional climate data means.

The actual predictions are presented in Section 2.7. At the bottom of the graphs are error bars showing the range of projections from the three models for each month. In general the models have greater agreement for the increase in minimum temperatures. For maximum temperature there is greater variation between the three models.

Projections of extreme temperature require a sophisticated approach. This report uses outputs from a decile-to-decile scaling technique to project the changes in frequency for (i) days over 40°C, and (ii) 3-5 consecutive days over 40°C[19]. Data from locations closest to the six sites are included to give an indication of the projected increase in extreme temperatures for 2035.

2.6.1 General guidance on interpreting the climate change projections

For each region the mean actual climate data, from 1961-1990, is shown in blue. The bars around these points show the variation over the three decades with the bottom and top bar representing the 10th and 90th percentile, respectively (e.g. Figure 7 and Figure 10).

What this means is that 8 years in 10 you would have experienced the temperature or rainfall conditions between the bottom and top bar; 1 in 10 years you would have experienced above (hotter or wetter), or below this range (cooler or drier).

The projected value for 2035 is shown in red. This value is for a single year and doesn't show the new variability expected. One of the features of climate change is that the climate variability is also expected to increase. This is particularly so for rainfall.

So when thinking about the projected climate for 2035 you will also need to consider what the variation will be. If we assume that 2035 is the average year and the variation remains the same then the 1 in 10 years, which are hotter or wetter, will be considerably greater than the mean for 2035. This is explored further below.

[19] Kevin Hennessy, John Clarke and Jim Ricketts, 2011. Methods for producing extreme temperature projections for Australia. CAWCR Technical Report No. 038.

2.6.2 What does a MEAN mean?

Climate information is presented as the mean (average) for a period, e.g. a month or year. By taking the mean, the highs and lows during the period are hidden in the mean. For vegetable growers these extremes can be disastrous. A run of very hot weather can cause damage and downgrade a crop, while an early or late frost can result in crop loss. Both events will hit the bottom line.

For each region the ***mean monthly*** maximum and minimum ***temperatures*** are presented. To understand what this actually means you need to dig a bit deeper. Small changes in a mean can have more of an impact than expected.

What do these predicted changes in temperature and variability mean for vegetable growers? To give an idea of what is predicted to occur, consider this case study of Manjimup, WA.

2.6.3 Manjimup case study, December 2012: Climate is what you expect – weather is what you get.

The average monthly temperature for December in Manjimup is 25.3°C and predicted to rise by 0.8°C to 26.1°C by 2035. This would mean that the number of hot Decembers (28°C average) will double from 1:10 to 1:5. In Figure 6 the increased risk of a hot December is shown by the red shaded area.

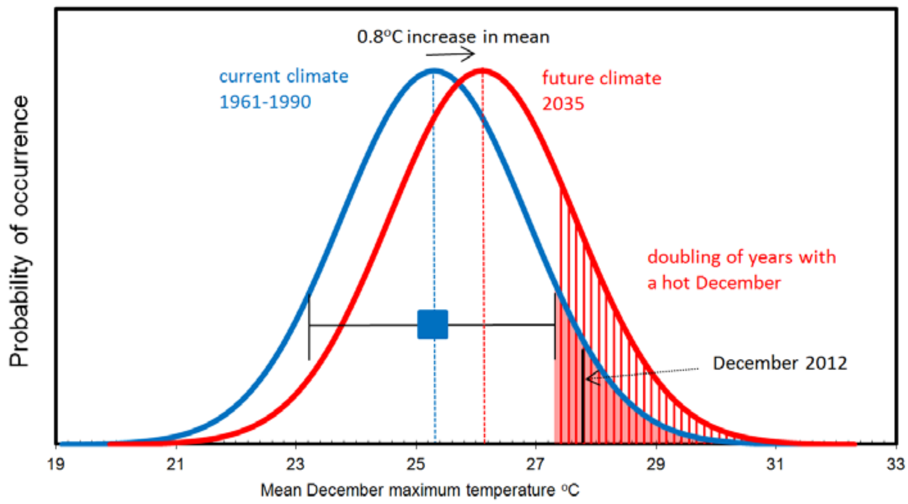

Figure 6 The December mean monthly maximum temperature for Manjimup during 1961-1990 and that projected for 2035. The shaded area marks the monthly maximum temperatures experienced one year in ten during 1961-1990, (i.e. the 90th percentile). The lines show the likely occurrence of these 'hot' Decembers under the future projected climate in 2035. The blue box and error bars represent the mean and 10th and 90th percentiles as shown in the following regional graphs.

Manjimup actually got a 1:10 hot December in 2012, and the average maximum temperature for the month was 27.8°C. But what did this mean? Figure 7 shows the actual daily maximum temperatures experienced in December, 2012.

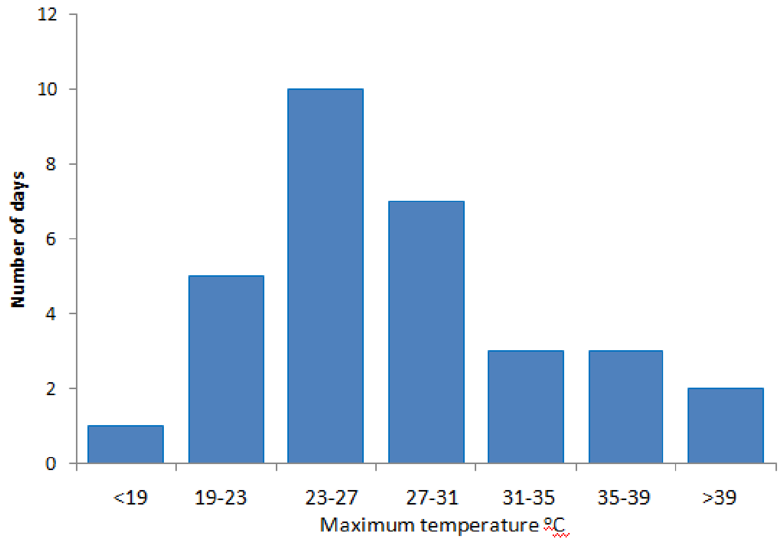

Figure 7. The distribution of daily maximum temperatures for Manjimup during December 2012. The monthly mean was 27.8°C but during December there were 5 days above 35°C.

While an average temperature of 27.8°C for December 2012 is only 2.5°C above the present average, and doesn't sound that bad, this included 5 days above 35°C and 2 days above 39°C.

What did this mean for the crops growing at the time?

The crops grown in the Manjimup over December are: lettuce, baby leaf crops (spinach, lettuce, rocket and others), brassicas and potatoes. Temperature requirements of these crops are shown in **Table 4** on page 80. In all cases, temperatures in the 35+°C range are disastrous for cool season vegetable and will result in crop failures.

In our study, similar scenarios are predicted to increase in Gatton, Hay, Werribee and Murray Bridge. The only region studied that was likely to escape major temperature spikes was Devonport.

2.6.4 Frost

Frost occurrence is a major risk to vegetable producers. Increases in the minimum temperature therefore might be a good thing if they reduce the frost incidence?

At the Managing Climate Variability program, scientists are currently looking at how frosts have changed over the last 20 years. They have found consistently that the period during which frosts can occur, the frost window, is much wider, particularly in the eastern parts of Australia[20]. This is despite an overall increase in mean minimum temperatures.

The seasonality of frosts has changed over the last 20 years. The analyses have revealed that in the east the frost window is both starting earlier (on average up to 10 days earlier by 2010) and ending later (up to 46 days later by 2010).

This means that frosts will be MORE of a risk in the future: the risk period will start earlier and finish later.

The pattern of later endings is consistent across much of southern Australia, whereas the earlier starts are more localised to western New South Wales and northern Victoria.

The frequency of more extreme cold temperatures is also on the rise across much of southern New South Wales and northern Victoria. An average increase of four frost days and five cold nights each decade has been identified since 1970.

The changes in the frost window, despite increases in mean temperature, are consistent with the expected increases in climate variability[21]. This is due to changes in regional weather patterns. The trend is that the band of high pressure, which normally sits across southern Australia has moved further south and intensified, allowing cold polar air to move onto the continent following the passage of any cold fronts. The trend is more significant in eastern parts, from New South Wales right down into Victoria and South Australia.

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20 Pers. Com. Beverly Henry, Program Leader Managing Climate Variability 2013.

21 Bradley Murphy & Bertrand Timbal 2008. A review of recent climate variability and climate change in south-eastern Australia. International Journal of Climatology 28:589-879.

2.6.5 Crop water use

For vegetable crops, water use is primarily determined by the demand from the atmosphere, rather than supply of water from the soil. Frequent irrigation ensures soil water is always available, except in circumstances of exceptional demand. This does assume that water is available for irrigation. As changes in the climate appear not to be having a large impact on the demand from the atmosphere, as outlined below, it is most likely that the largest impact on crop water use will be the availability of water for irrigation. For each of the regions the supply of water is considered.

Growers will need to irrigate crops to keep them cool during heatwaves, e.g. the December 2012 heatwave in Manjimup. This additional irrigation requirement will place additional demand on water resources when supply is likely to already be under pressure during a "hot" period.

The atmospheric demand for water is estimated by the potential evaptoranspiration (PET; calculated by BoM using FAO 56 Penman – Monteith). To understand the possible impact of changes in the climate on crop water use some understanding of FAO 56 Penman – Monteith is required.

The impact of changes to the climate on crop water use is not simple. This is because four factors influence PET: sunshine Rs; temperature T; wind speed U2; and relative humidity RH (Figure 8). Projected increases in temperature can be offset by decreases in wind or sunshine, due to an increase in cloudy conditions.

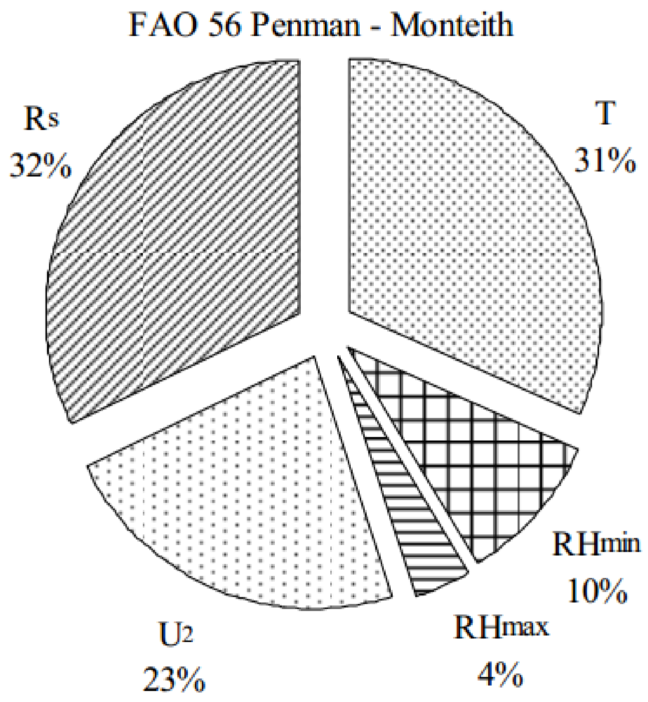

Figure 8. Relative sensitivity of FAO Penman-Monteith potential evapotranspiration to key climate parameters of: R_s – solar radiation; U^2 - wind speed; T – temperature mean; $RH_{min\ and\ max}$ - relative humidity minimum and maximum[22].

Over the past few decades PET has been falling, despite increases in temperature. Between 1981 –2006 Australiawide PET declined by 20mm[23]. Thus while increasing temperature would have increased PET, by about 25mm, this was more than offset by changes in wind speed, relative humidity and sunshine. As a result a reduction in PET was observed, which is consistent with long-term reduction in pan evaporation across Australia[24].

The inter-play between temperature and other climate factors means that change in PET under changes in the projected climate are likely to be small (Figure 9). For 2030, the best estimate suggests only a 2-4% increase in PET in the vegetable growing regions.

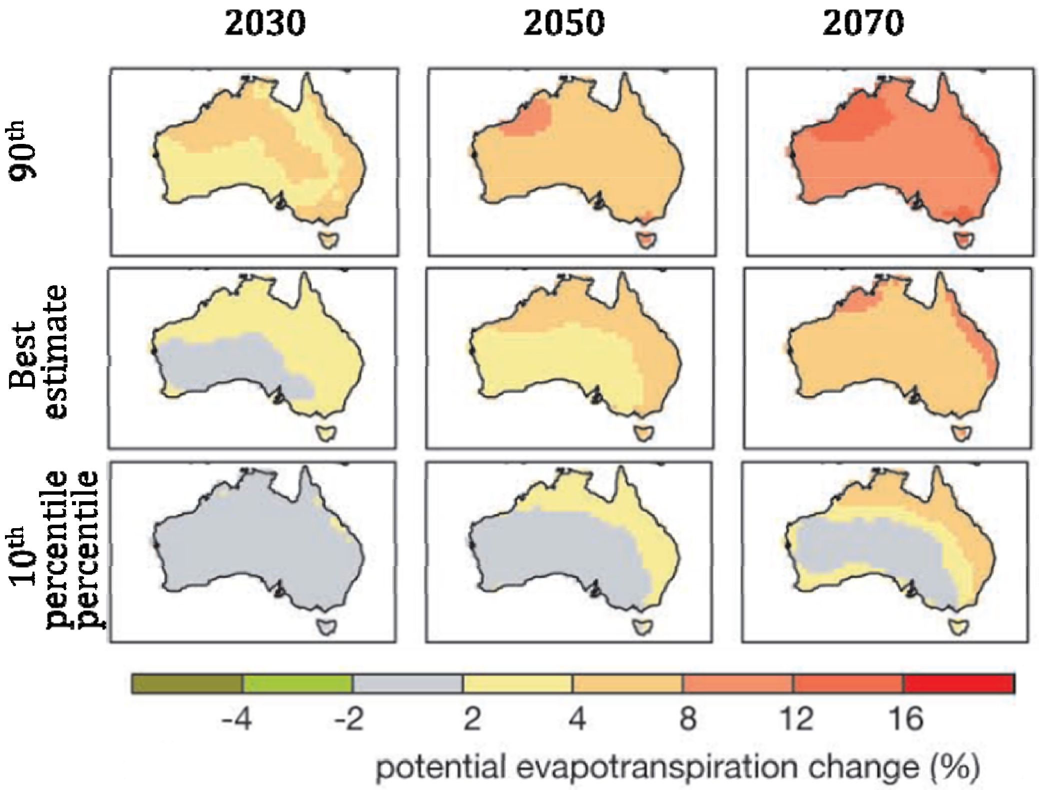

Figure 9. Projected changes in annual potential evapotranspiration under the A2 global emission scenario[25].

[22] V Ambas & E Baltas 2012. Sensitivity analysis of different evapotranspiration methods using a new sensitivity coefficient. Global NEST Journal, Vol 14, No 3, pp 335-343, 2012

[23] Donohue, R.J., McVicar, T.R. and Roderick, M.L., 2009. Generating Australian potential evaporation data suitable for assessing the dynamics in evaporative demand within a changing climate, December 2009.CSIRO

[24] Roderick ML, Farquhar G (2006) A physical analysis of changes in Australian pan evaporation. Land & Water Australia Project No. ANU49. CRC for Greenhouse Accounting.

[25] Potential evapotranspiration supplementary material 2007. Change Projections of the Climate Change in Australia. Technical Report CSIRO 2007.

2.7 Temperature and rainfall projections to 2035 for vegetable growing regions in Australia

2.7.1 Summary of predicted changes

Southern winter production areas such as Werribee, Cranbourne and East Gippsland will benefit from higher average winter temperatures (0.5–1.2°C). These areas are used for summer production of leafy vegetables and will also experience higher average summer maximum temperatures (0.6–1.3°C), making them more marginal. The northern cool season production areas such as Stanthorpe and the Atherton tableland will become more marginal for cool season crops.

Central and northern regions used for winter and transition period production of cool season crops will become more marginal at the boundaries of the seasons (early and late). Examples of these areas are the Lockyer Valley in spring/ autumn for leafy vegetables and brassicas, central highlands and mid western areas of NSW.

Warm season crops in summer production areas will be less affected. There will be some effects on crops such as tomatoes and capsicums where pollination is adversely affected by average temperatures above 27°C, and there will be a marginal reduction in the length of production seasons.

The seasonality of frosts has already changed over the last 20 years, and the frost window will be longer in the future.

Some examples of expected regional changes in temperature are shown in Table 3.

Table 3 Expected changes in temperature and rainfall for the six regions

Region	Change in maximum temperatures (Monthly av. °C)	1:10 year maximum temperatures (February)	Risk of 3-5 days > 40°C		Rainfall
			2012	2035	
Gatton	+ 1.1	+ 3.1	1:33	1:10	- 3%
Hay	+ 1.1	+ 4.1	1:5	1:2	- 5%
Werribee	+ 1.0	+ 3.5	1:5	1:2	- 8%
Manjimup	+ 0.8	+ 2.8	1:5	1:3	- 7%*
Murray Bridge	+ 0.9	+ 3.8	0	1:5	- 8%
Devonport	+ 0.6	+ 1.7	0	0	- 6%

*SE Western Australia: up to 10% rainfall reduction in winter on top of -15% since 1988

2.7.2 Manjimup

2.7.2.1 Projected changes in climate

By 2035 the projected increase in the annual maximum temperature ranges from 0.6 to 1.0°C, as estimated by the three models. The increase in the mean monthly maximum is most pronounced from May through to September (Figure 10).

The projections for extreme temperatures is that the number of days above 40°C will increase from 3.8 to 5.3. The average run of 3-5 days above 40°C will increase from the current 0.2 to 0.3 (i.e from 1 in 5 years to 1 in 3 years).

The minimum temperature is projected to increase by between 0.5 and 0.9°C for 2035. These increases are reasonably uniform across the year, including summer.

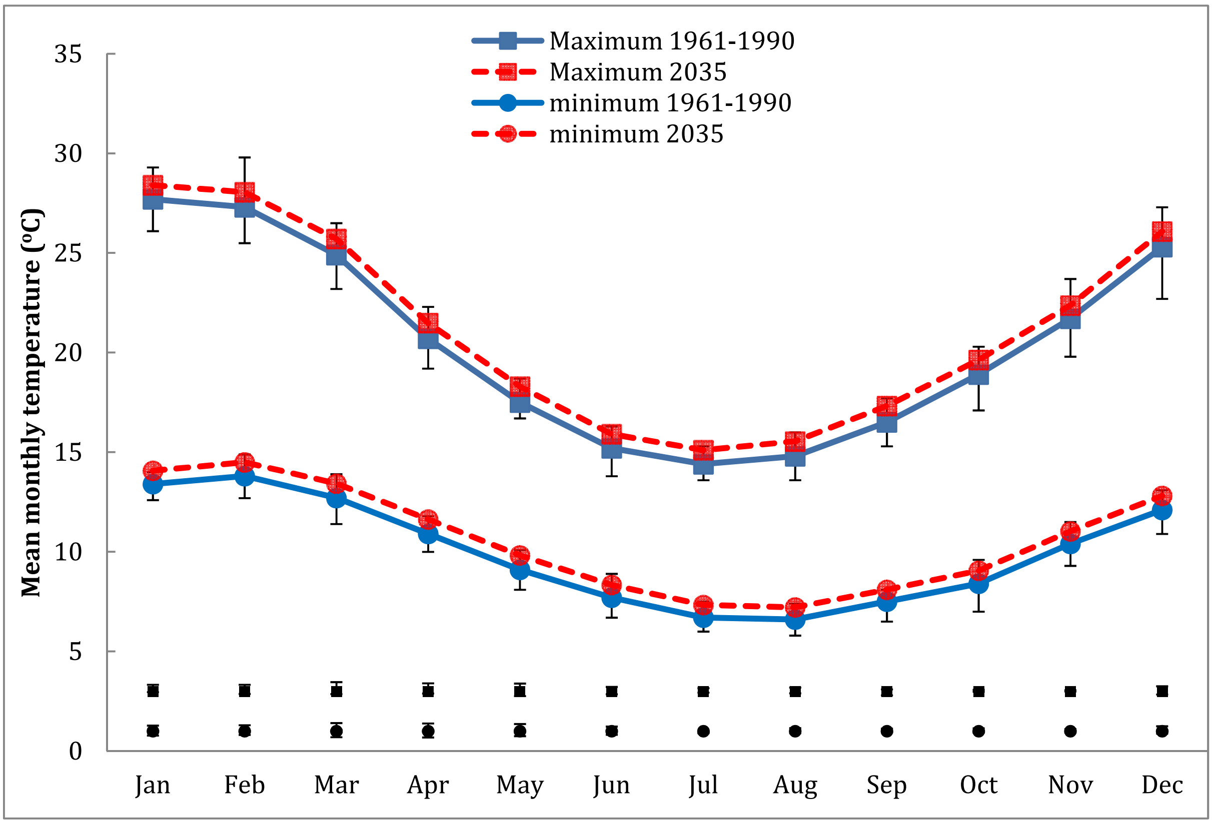

Figure 10. The mean monthly maximum and minimum temperatures is shown for the Manjimup region. The average for the 1961-1990 period is shown in blue, together with 10th and 90th percentiles, as indicated by the bottom and top bars, respectively. The projected mean monthly temperature for 2035 is shown in red. The error bars at the bottom indicate the variation between the three model projections.

A decrease in the annual rainfall, ranging from 5-9% is projected by 2035. The decrease in mean monthly rainfall is most noticeable in winter with a decrease projected ranging from 7 to 10% (Figure 11).

The rainfall in winter has already declined by 15% since 1988, indicating that the projections appear to be under estimating the impact on rainfall for southwest WA.

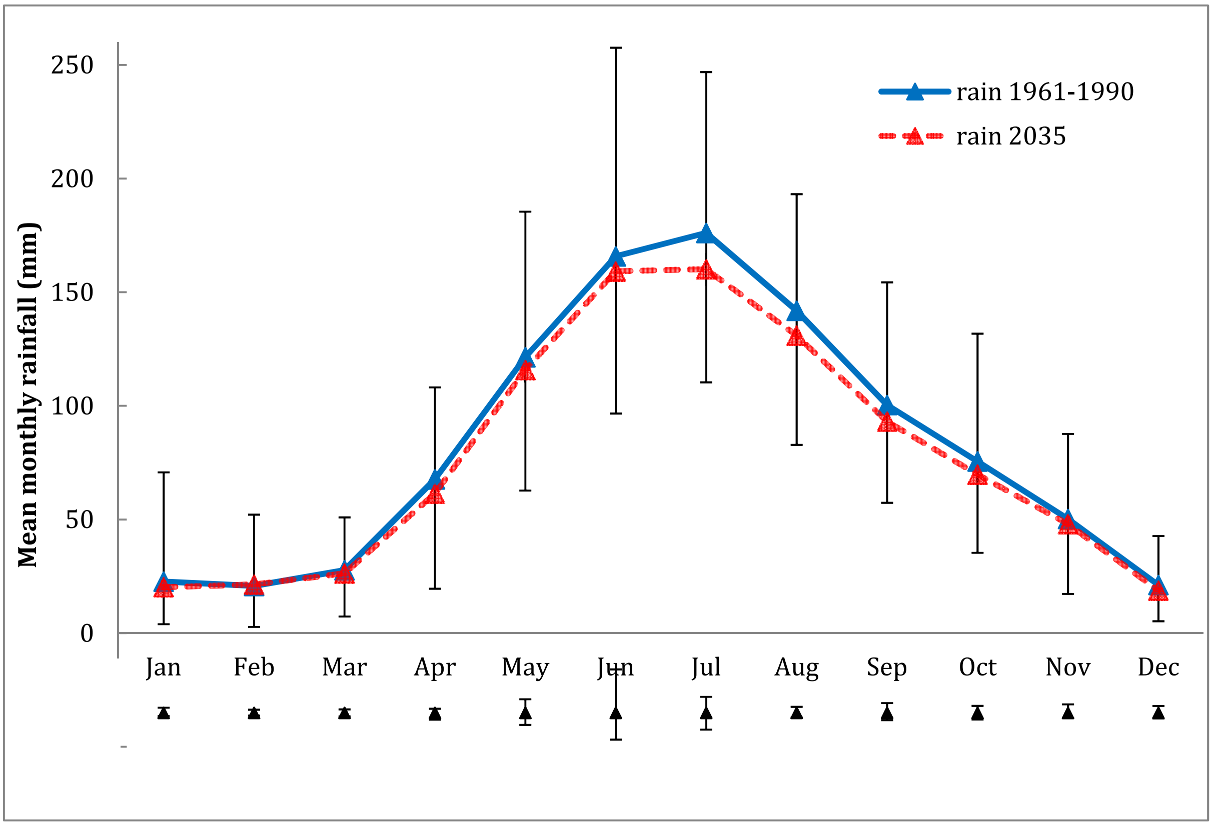

Figure 11. The mean monthly rainfall is shown for the Manjimup region. The average for the 1961-1990 period is shown in blue, together with 10th and 90th percentiles, as indicated by the bottom and top bars, respectively. The projected mean monthly rainfall for 2035 is shown in red. The error bars at the bottom indicate the variation between the three model projections.

2.7.2.2 Manjimup: Potential impacts on vegetable production – Discussion Starters

Growing conditions

- The warmer winters and into spring may reduce the winter crop window.
- Manjimup currently supplies summer leaf vegetables for the fresh WA market. Increases in extreme temperatures will impact on the quality of these crops.

Water

- Vegetable production in Manjimup is dependent on localised surface water run-off and on-site storage. Any changes to either water supply or irrigation demand would have the greatest impact on the vegetable industry. Only minor increases in crop water use are expected.
- The rainfall projections for 2035 indicate that the trend for decreasing rainfall observed from 1988-2012 (Table 2) will continue (Figure 11).
- Reductions in winter rainfall will reduce the run-off available for storage and irrigation. The impact on surface run-off could be larger than the impact of rainfall, i.e. depending on the catchment a 7-10% reduction in rainfall may result in a substantially greater reduction in run-off. For example, the 10-15% decrease in rainfall resulted in run-off decreasing by a half.
- The period 1997-2007 was dry with substantial declines in run-off. This period approximates the sort of run-off expected under 2035 projections, with only a small (<5%) further declined in run-off[26].

[26] CSIRO (2009) Water yields and demands in south-west Western Australia. A report to the Australian Government from the CSIRO. South-West Western Australia Sustainable Yields Project, CSIRO.

2.7.3 Gatton

2.7.3.1 Projected changes in climate

For 2035 the Gatton region, together with Hay, has one of the largest projected increases in annual temperature. The annual maximum and minimum temperatures are projected to increase by between 0.7 to 1.4°C, and 0.8 to 1.2°C, respectively, as estimated by the three models. Increases in the mean monthly maximums are strongest for the cooler months of May – August (Figure 12).

During these months the 2035 mean maximum temperature will be similar to that which occurred every one year in ten under the current climate. By 2035 the one-in-ten-year projected mean monthly maximum temperatures for January is projected to exceed 33.7°C.

The projections for extreme temperatures, from nearby Amberley, is that days above 40°C will increase from 0.8 to 1.2 days per year. The average run of 3-5 days above 40°C will increase from the current 0.03 to 0.10 (i.e. from 1 in 33 years to 1 in 10 years).

Relatively uniform increases in minimum temperatures of between 0.8 and 1.2°C are projected for 2035.

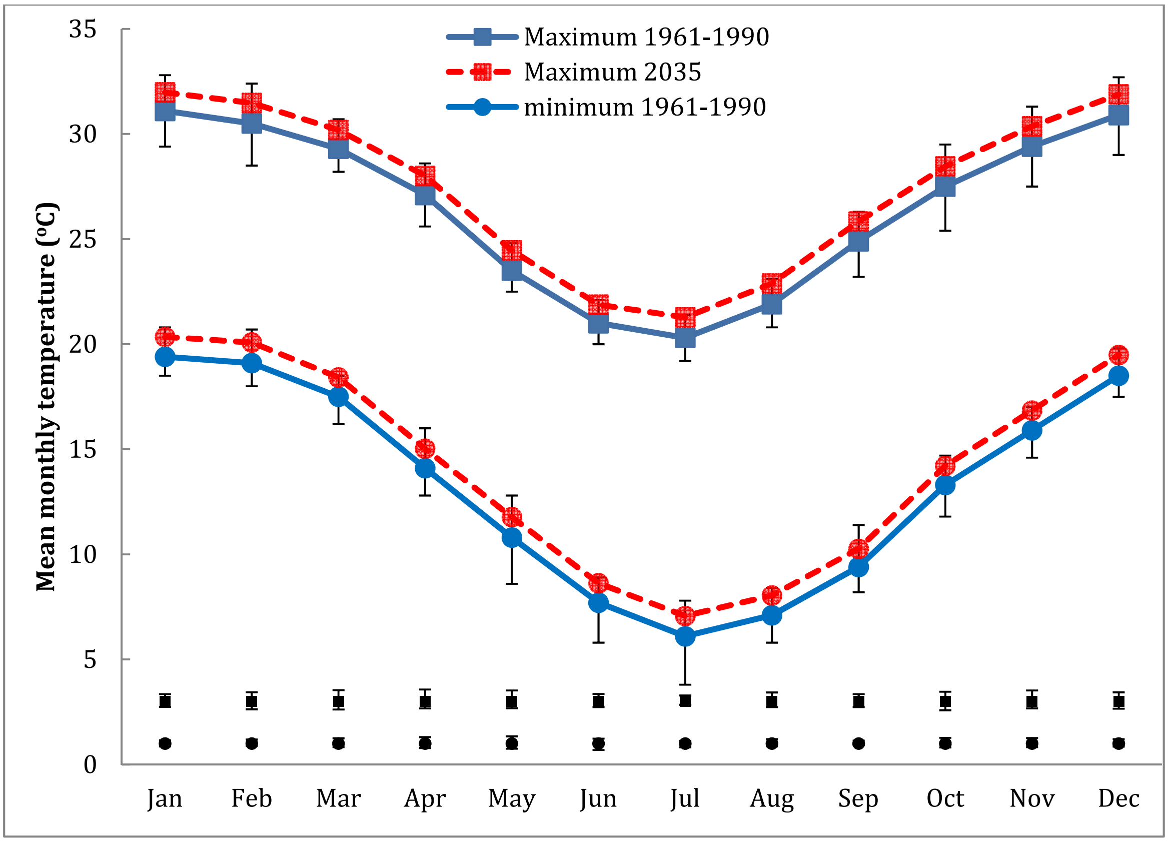

Figure 12. The mean monthly maximum and minimum temperatures are shown for the Gatton region. The average for the 1961-1990 period is shown in blue, together with 10th and 90th percentiles, as indicated by the bottom and top bars, respectively. The projected mean monthly temperature for 2035 is shown in red. The error bars at the bottom indicate the variation between the three model projections.

A feature of mean monthly rainfall is the high level of year-to-year variation (Figure 13). This is very evident in the Gatton region. The 2035 projection shows little change in annual rainfall with model projections ranging from a 7% increase to a 10% decrease. The biggest impact will potentially be the increase in variations, i.e. droughts more severe and longer and the wet periods, wetter. This is consistent with the rainfall in the region over the last decade.

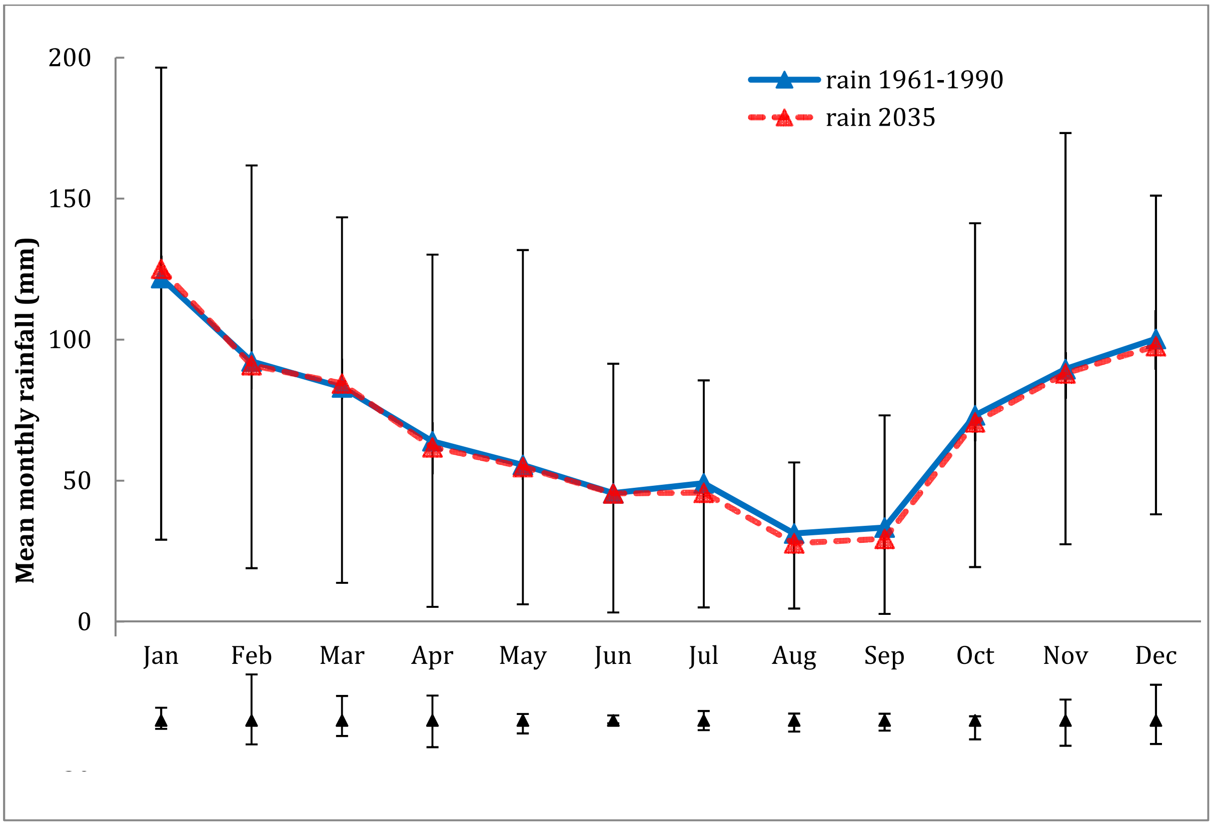

Figure 13. The mean monthly rainfall is shown for the Gatton region. The average for the 1961-1990 period is shown in blue, together with 10th and 90th percentiles, as indicated by the bottom and top bars, respectively. The projected mean monthly rainfall for 2035 is shown in red. The error bars at the bottom indicate the variation between the three model projections.

2.7.3.2 Gatton: Potential impacts on vegetable production – a discussion starter

Growing conditions

- The higher projected maximum temperatures are likely to reduce the winter growing window for current varieties of lettuce and brassicas.
- The current harvest window of April to October is likely to be reduced, although not by the 3 weeks indicated by previous studies, which used the worst-case scenario emission scenarios and only one model with a high climate sensitivity[27].
- Late-summer flooding rains, which may increase in frequency, will impact on the preparation and establishment of winter crops.

Water

- Vegetable production in Gatton is dependent on groundwater pumping from localised shallow alluvial aquifers, limited surface water harvesting and on-site storage. Any changes to either water supply or irrigation demand would have a significant impact on the vegetable industry. Only minor increases in crop water use are expected.
- The rainfall projections for 2035 indicate there will be little change in annual rainfall (Figure 13). The greatest impact will continue to be the variability of rainfall. Substantial reduction in groundwater availability occurred during the recent long drought in the Lockyer Valley[28]. Although rainfall is not expected to change, the increase in variability could see such prolonged droughts occur more frequently.

[27] Peter Deuter, Neil White and David Putland. 2012. Critical temperature thresholds Case study Lettuce.
[28] Groundwater responses to the 2010–11 floods, December 2011. National water Commission.

2.7.4 Hay

2.7.4.1 Projected changes in climate

For 2035 the Hay region, together with Gatton, has one of the largest projected increases in annual temperature. The annual maximum and minimum temperatures are projected to increase by between 0.7 to 1.4°C, and 0.6 to 1.2°C, respectively, as estimated by the three models. Increases in the mean monthly maximum are reasonably uniform across the year (Figure 14).

In 2035 the 1-in-10-year projected mean monthly maximum temperature for January is projected to exceed 36.7°C. The projections for extreme temperatures, from nearby Deniliquin, is that days above 40°C will increase from 4.5 to 6.8 days. The average run of 3-5 days above 40°C will increase from the current 0.3 to 0.6 (i.e. from 1 in 5 years to 1 in 2 years).

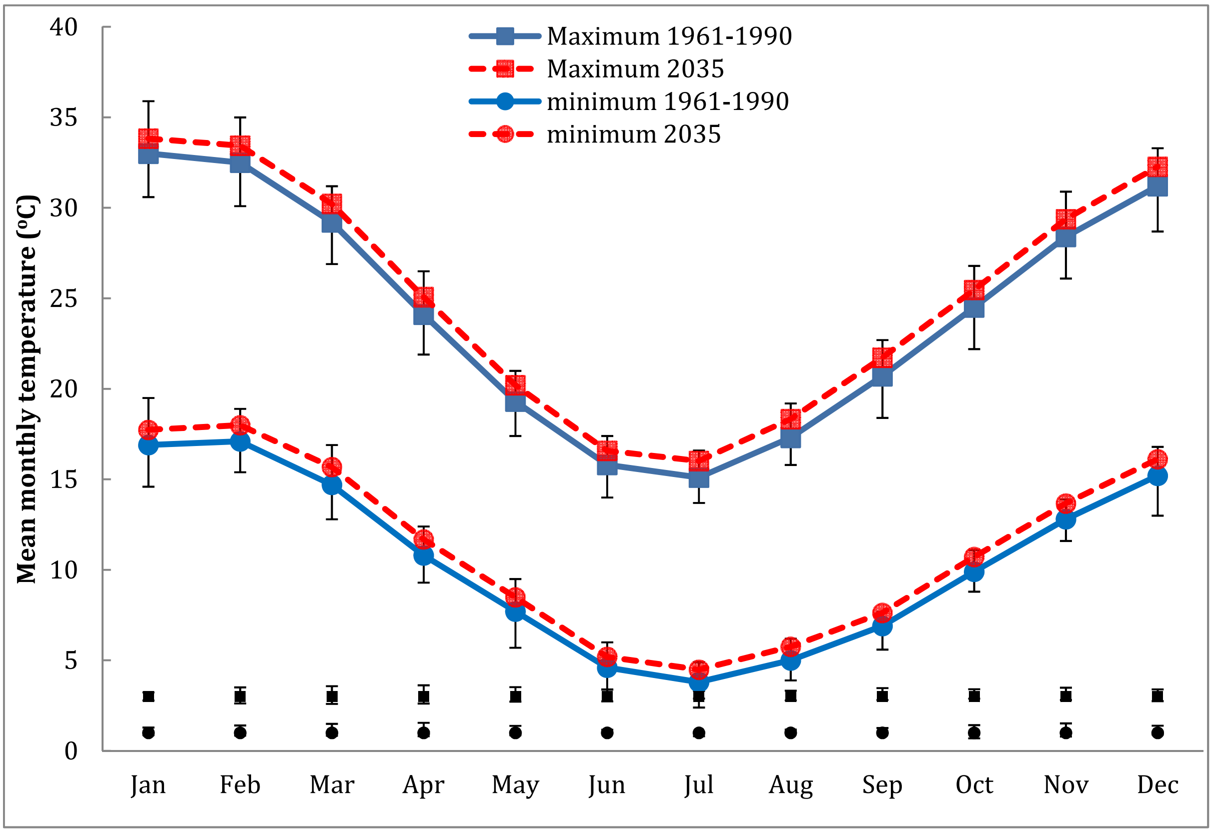

Figure 14. The mean monthly maximum and minimum temperatures is shown for the Hay region. The average for the 1961-1990 period is shown in blue, together with 10th and 90th percentiles, as indicated by the bottom and top bars, respectively. The projected mean monthly temperature for 2035 is shown in red. The error bars at the bottom indicate the variation between the three model projections.

The mean monthly minimum temperature is projected to increase by between 0.6 and 1.2°C by 2035. These increases are greatest in winter and spring with mean monthly minimum temperatures similar to those experienced in 1 or 2 years in 10 under the current climate.

Despite the increase in mean monthly minimums the frost window may actual increase. Over the last 20 years the frost window has increased due to earlier starts in western NSW and later endings. The intensification and southern movement of the band of high pressure has been responsible for the lengthening of the frost window. The climate models project this trend to continue out to 2035.

The 2035 projection shows little change in annual rainfall with model predictions ranging from a 2% increase to a 12% decrease (Figure 15). Where a decrease is projected, this is concentrated in late winter and spring.

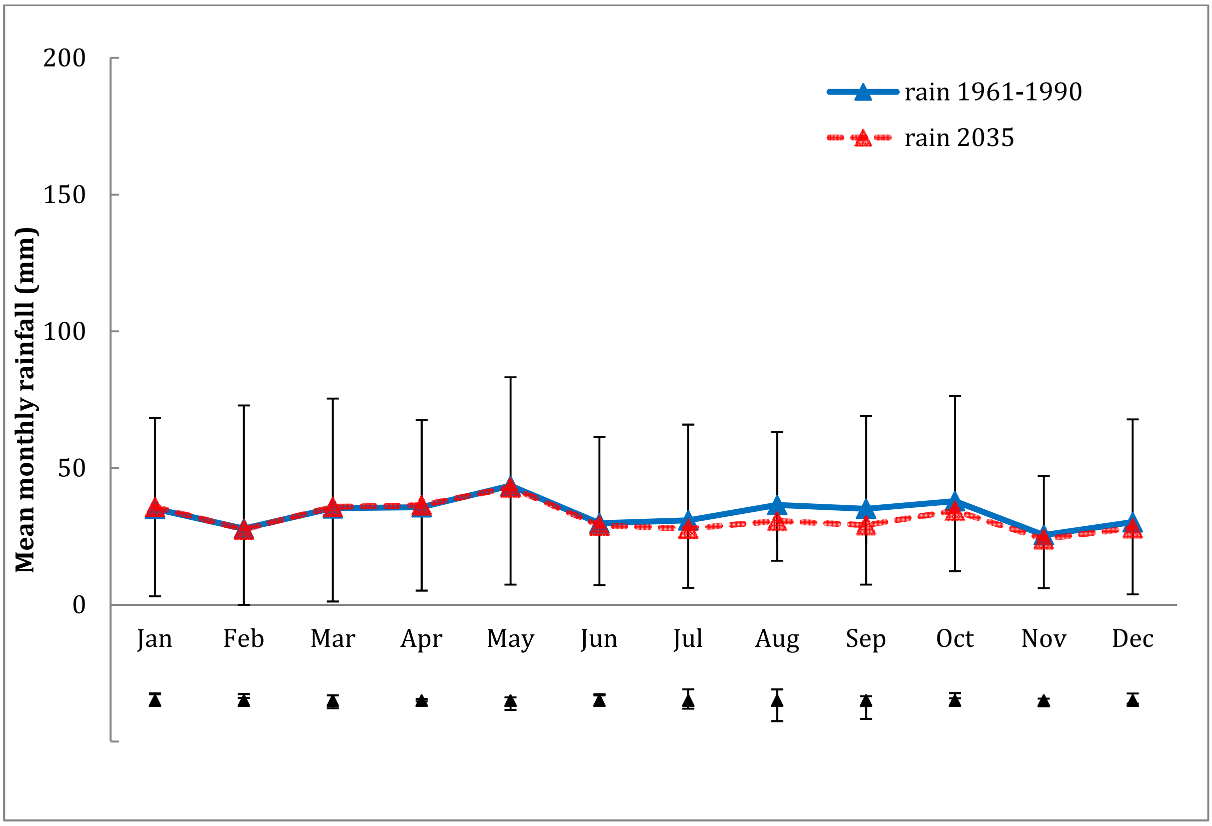

Figure 15. The mean monthly rainfall is shown for the Hay region. The average for the 1961-1990 period is shown in blue, together with 10th and 90th percentiles, as indicated by the bottom and top bars, respectively. The projected mean monthly rainfall for 2035 is shown in red. The error bars at the bottom indicate the variation between the three model projections.

2.7.4.2 Hay: Potential impacts on vegetable production – a discussion starter

Growing conditions

- The Hay region has already seen a transformation in production with a shift from vegetable cropping to other summer crops such as cotton. Such transformations are driven by a number of factors such as markets, labour and water availability. Changes in climate are just one of the factors in such transformations of a region.
- Looking forward to 2035 the Hay region is projected to see an increase in summer extremes that will make producing quality summer crops such as cucurbits difficult. Providing water is available such high temperatures may have minimal effect on yield.
- May adversely affect fruit quality in melons and may also adversely affect kernel fill in sweet corn.
- The potential increase in the frost window may have significant implications for the Hay region. The possible reason why this is occurring and expected to continue, despite a projected general increase in temperature, is outlined in section 2.6.4. The consequence will vary for crops and their sensitivity to frosts. But the potential for crop damage to increase is likely as generally warmer conditions allow for new growth, which is then susceptible to late and early "out of season" frosts.

Water availability

- The good news is that 2035 projections for water availability in the Murrumbidgee is less severe than in the recent past. During 1997-2006 average surface water availability declined by 30%. The best estimate for 2035 is a 9% reduction in surface water availability[29].
- The Hay region is dependent on river pumping from the Murrumbidgee River. Thus changes in local rainfall have little impact on water availability for irrigation. However, the impact of regional climate change is expected to impact on the reliability of water licences in the Murrumbidgee.
- During the recent drought, for the first time high-security water holders did not receive their full allocation, with this dropping to 90% in 2006/07 and 2007/08, while general-security water holders received only 10% and 13%, respectively.

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[29] CSIRO 2008. Water Availability in the Murrumbidgee. CSIRO Murray0Darling Basin Sustainable Yields Project.

2.7.5 Werribee

2.7.5.1 Projected changes in climate

For 2035 the projected increase in the annual maximum temperature ranges from 0.6 to 1.3°C, as estimated by the three models. The increase in the mean monthly maximum is reasonably uniform across the year (Figure 16).

The projections for extreme temperatures, from nearby Melbourne, is that days above 40°C will increase from 1.3 to 2.0 days.

The annual minimum temperature is projected to increase by between 0.5 and 1.0°C by 2035. These increases are greatest in late winter and spring with the mean monthly minimum temperatures similar to those experienced in 1 or 2 years in 10 under the current climate.

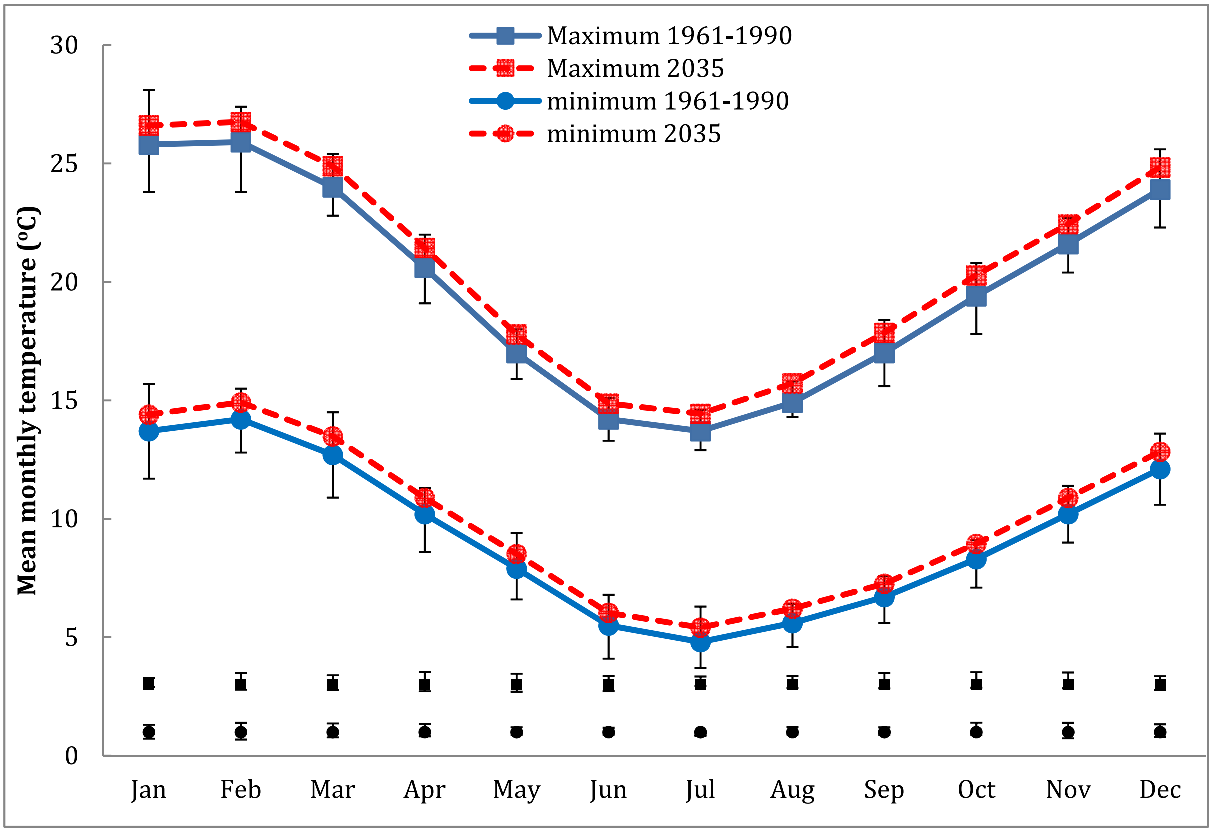


Figure 16. The mean monthly maximum and minimum temperatures is shown for the Werribee region. The average for the 1961-1990 period is shown in blue, together with 10th and 90th percentiles,, as indicated by the bottom and top bars, respectively. The projected mean monthly temperature for 2035 is shown in red. The error bars at the bottom indicate the variation between the three model projections.

The annual rainfall is projected to decrease by between 2 to 14% by 2035. The decrease in mean monthly rainfall is most noticeable in spring (Figure 17). The three models project the mean monthly rainfall to decrease by between 6 and 19% during spring.

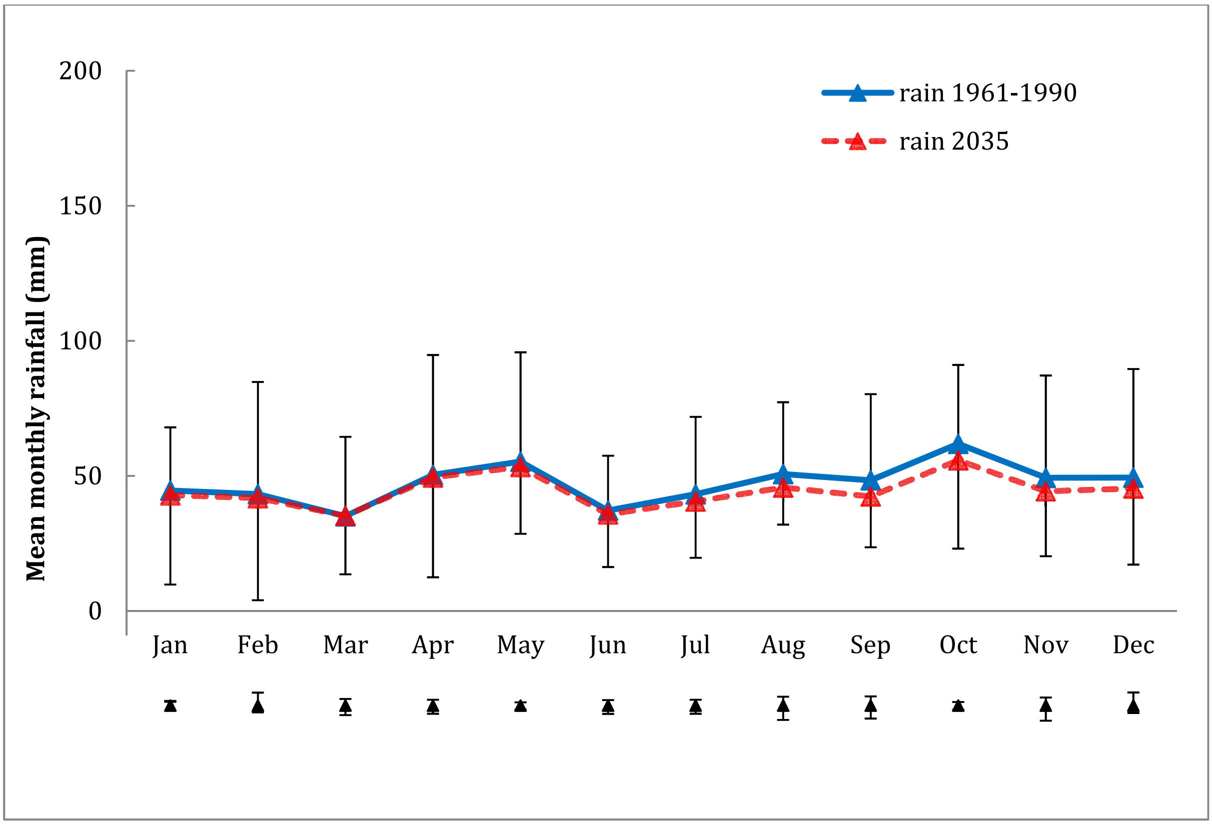


Figure 17. The mean monthly rainfall is shown for the Werribee region. The average for the 1961-1990 period is shown in blue, together with 10th and 90th percentiles, as indicated by the bottom and top bars, respectively. The projected mean monthly rainfall for 2035 is shown in red. The error bars at the bottom indicate the variation between the three model projections.

2.7.5.2 Werribee: Potential impacts on vegetable production – a discussion starter

Growing conditions

- The winter crops of brassicas may benefit from the warmer winter temperatures but this will be at the expense of reducing the season length. Head lettuce development may benefit from the warmer temperatures in winter.

Water supply

- Werribee relies on a mix of surface, ground and recycled water for irrigation with water quality being a significant issue. The surface and groundwater are reliant on local rainfall for run-off and to recharge the aquifer.
- Annual rainfall is projected to decrease by between 2-14%. From 1997 – 2009 the rainfall average was 25% lower than the 1990 base-year average, resulting in an increased reliance on recycled water and a decline in water quality.

2.7.6 Murray Bridge

2.7.6.1 Projected changes in climate

For 2035 the projected increase in the annual maximum temperature ranges from 0.6 to 1.1°C, as estimated by the three models. Increases in the mean maximum are reasonably uniform across the year (Figure 18).

The projections for extreme temperatures, from Adelaide, is that days above 40°C will increase from 2.3 to 3.6 days. The average run of 3-5 days above 40°C will increase from the current 0.0 to 0.2 (i.e. from none to 1 in 5 years).

The 2035 projected increase in the annual minimum temperature ranges between 0.5 and 0.9°C. The projected increase in mean monthly minimum temperatures is greatest in late winter and spring. During these months, mean monthly minimum temperatures will be similar to those experienced in 1 or 2 years in 10 under the current climate.

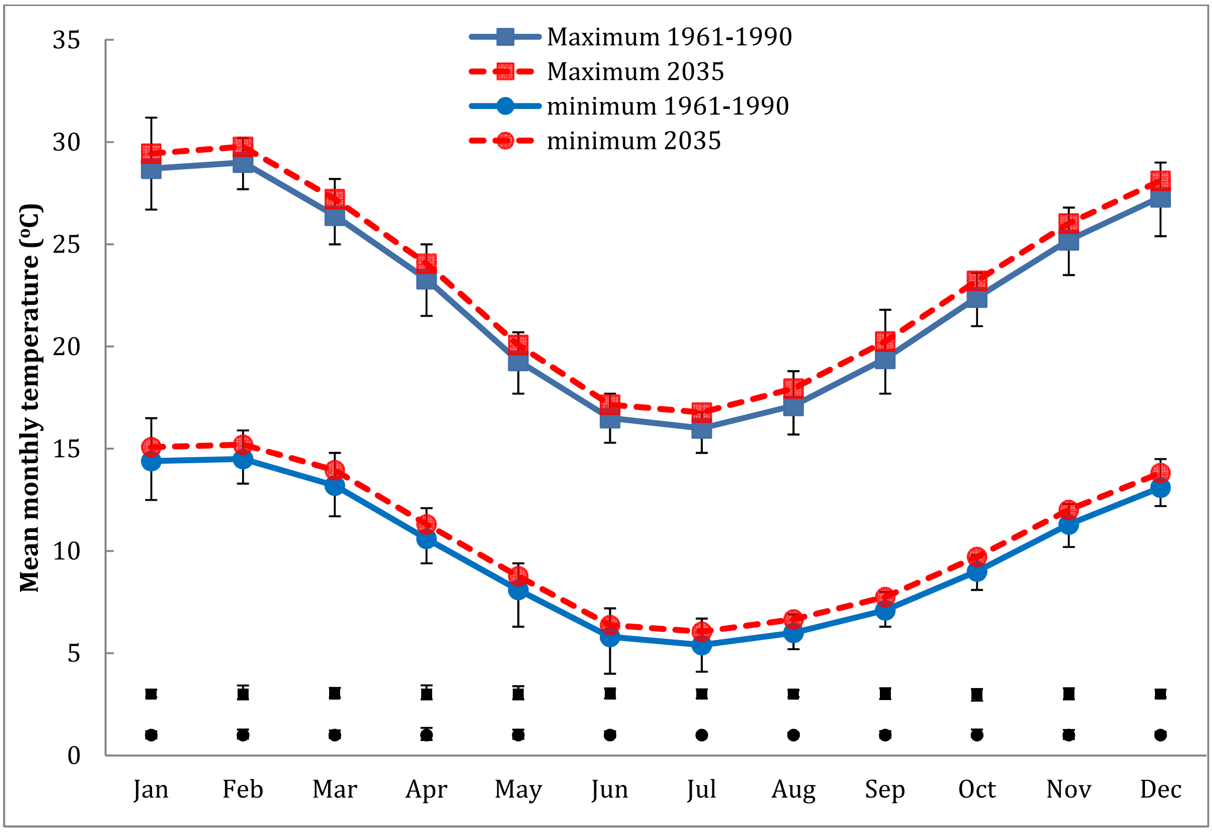


Figure 18. The mean monthly maximum and minimum temperatures is shown for the Murray Bridge region. The average for the 1961-1990 period is shown in blue, together with 10th and 90th percentiles, as indicated by the bottom and top bars, respectively. The projected mean monthly temperature for 2035 is shown in red. The error bars at the bottom indicate the variation between the three model projections.

A decrease in the annual rainfall, ranging from 0 to 15% is projected for 2035. The decrease in mean monthly rainfall is most noticeable in spring (Figure 19). During this period the mean monthly rainfall is projected to decrease by between 6 and 21%.

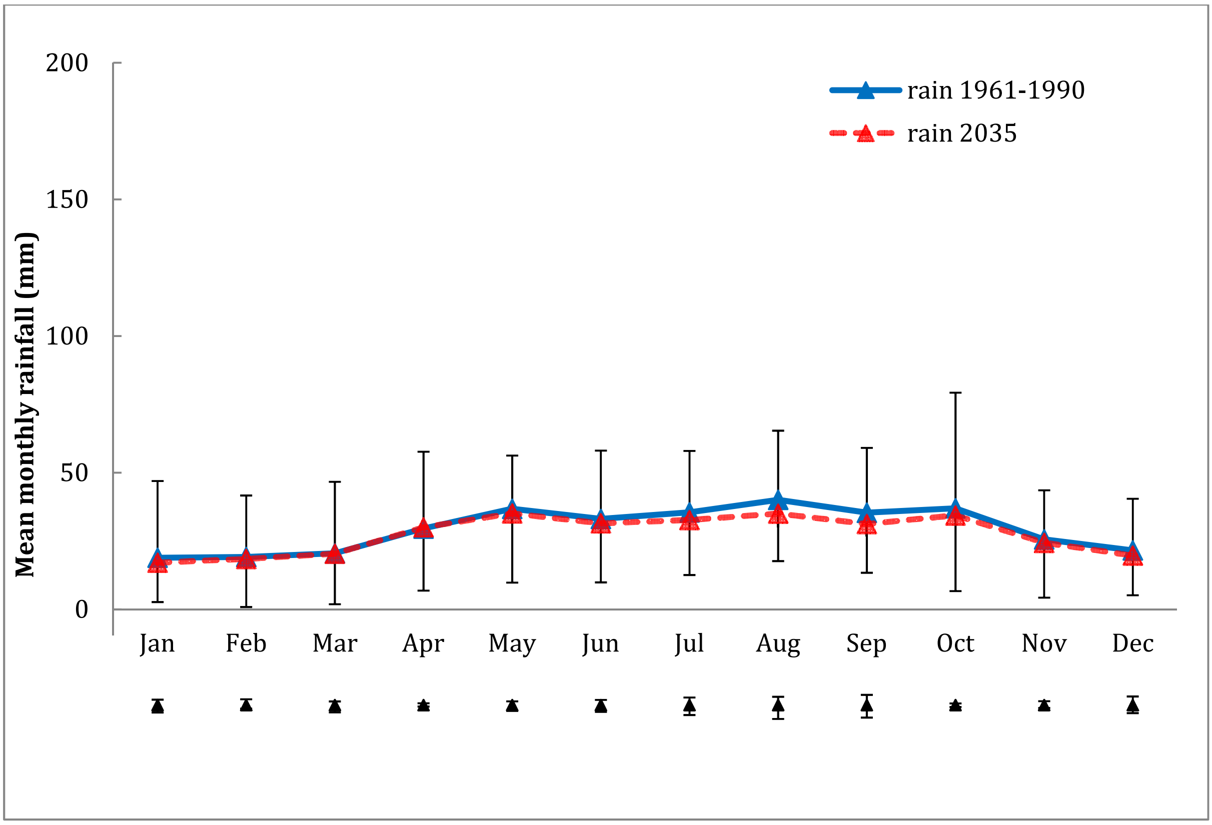


Figure 19. The mean monthly rainfall is shown for the Murray Bridge region. The average for the 1961-1990 period is shown in blue, together with 10th and 90th percentiles, as indicated by the bottom and top bars, respectively. The projected mean monthly rainfall for 2035 is shown in red. The error bars at the bottom indicate the variation between the three model projections.

2.7.6.2 Murray Bridge: Potential impacts on vegetable production – a discussion starter

Growing conditions

- The increase in summer temperatures, in particular the extremes, will impact on crops that mature over summer.
- The potential increase in the frost window may have significant implications for the Murray Bridge region. The possible reason why this is occurring and expected to continue, despite a projected general increase in temperature, is outlined in section 2.6.4. The consequence will vary for crops and their sensitivity to frosts. However, the potential for crop damage to increase is likely, as generally warmer conditions allow for new growth which is then susceptible to late and early "out of season" frosts.

Water availability

- The Murray Bridge region is dependent on river pumping from the Murray River. Thus changes in local rainfall have little impact on water availability for irrigation. Instead Murray Bridge is dependent on rainfall predominantly in NSW and Victoria to supply irrigation water.
- The 2035 projections for water availability in the Murray are less severe than in the recent drought. During 1997-2006 average surface water availability declined by 30%. The best estimate for 2035 is a 14% reduction in surface water availability[30].

[30] CSIRO 2008. Water Availability in the Murray. CSIRO Murray-Darling Basin Sustainable Yields Project

2.7.7 Devonport

2.7.7.1 Projected changes in climate

For 2035 the projected increase in the annual maximum temperature ranges from 0.2 to 1.0°C, as estimated by the three models, the least of all the regions.

The projections for extreme temperatures, from Lowhead, are that the maximum temperature will not exceed 40°C.

The annual minimum temperature is projected to increase by between 0.2 and 0.8°C for 2035 (Figure 20). These increases in mean annual monthly temperatures are more pronounced in winter and spring.

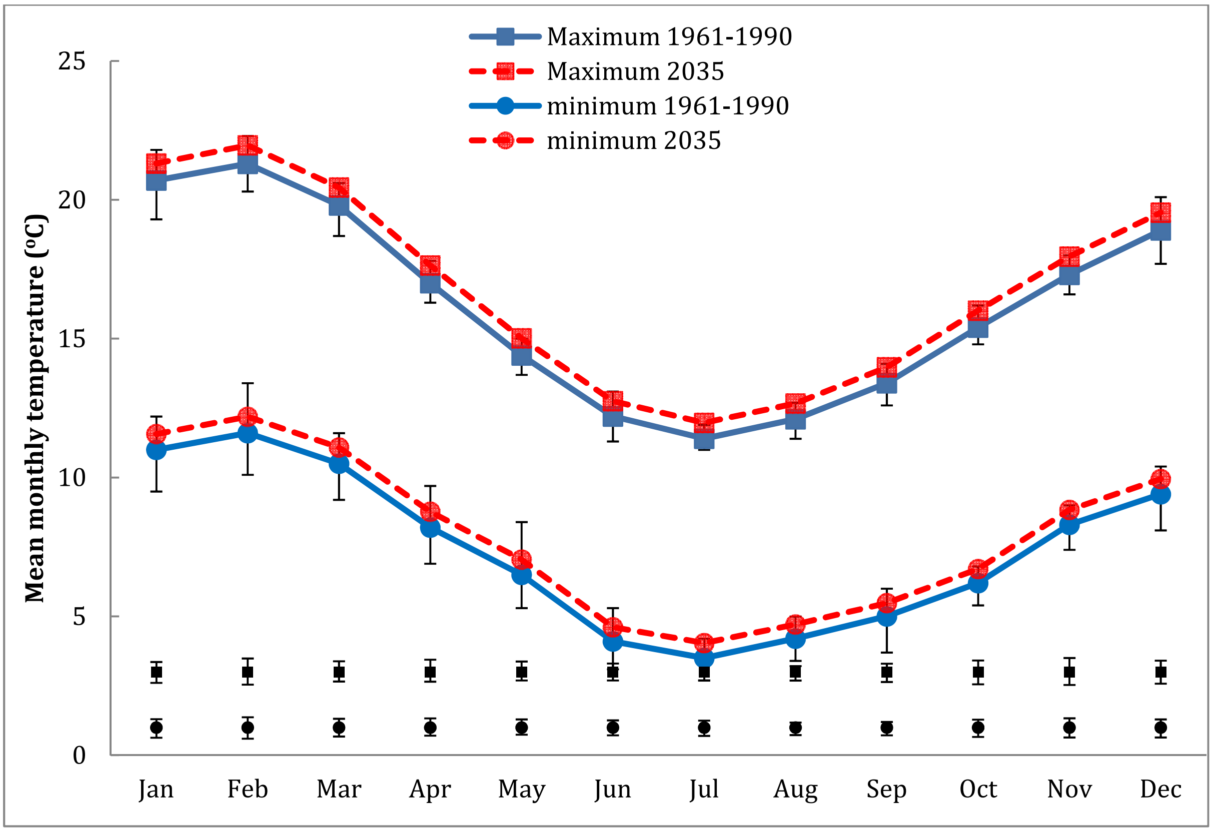


Figure 20. The mean monthly maximum and minimum temperatures is shown for the Devonport region. The average for the 1961-1990 period is shown in blue, together with 10th and 90th percentiles, as indicated by the bottom and top bars, respectively. The projected mean monthly temperature for 2035 is shown in red. The error bars at the bottom indicate the variation between the three model projections.

A decrease in the annual rainfall, ranging from 1 to 11% is projected by 2035. The decrease in rainfall is most noticeable in spring with mean monthly rainfall projected to decrease by between 3 and 17% (Figure 21).

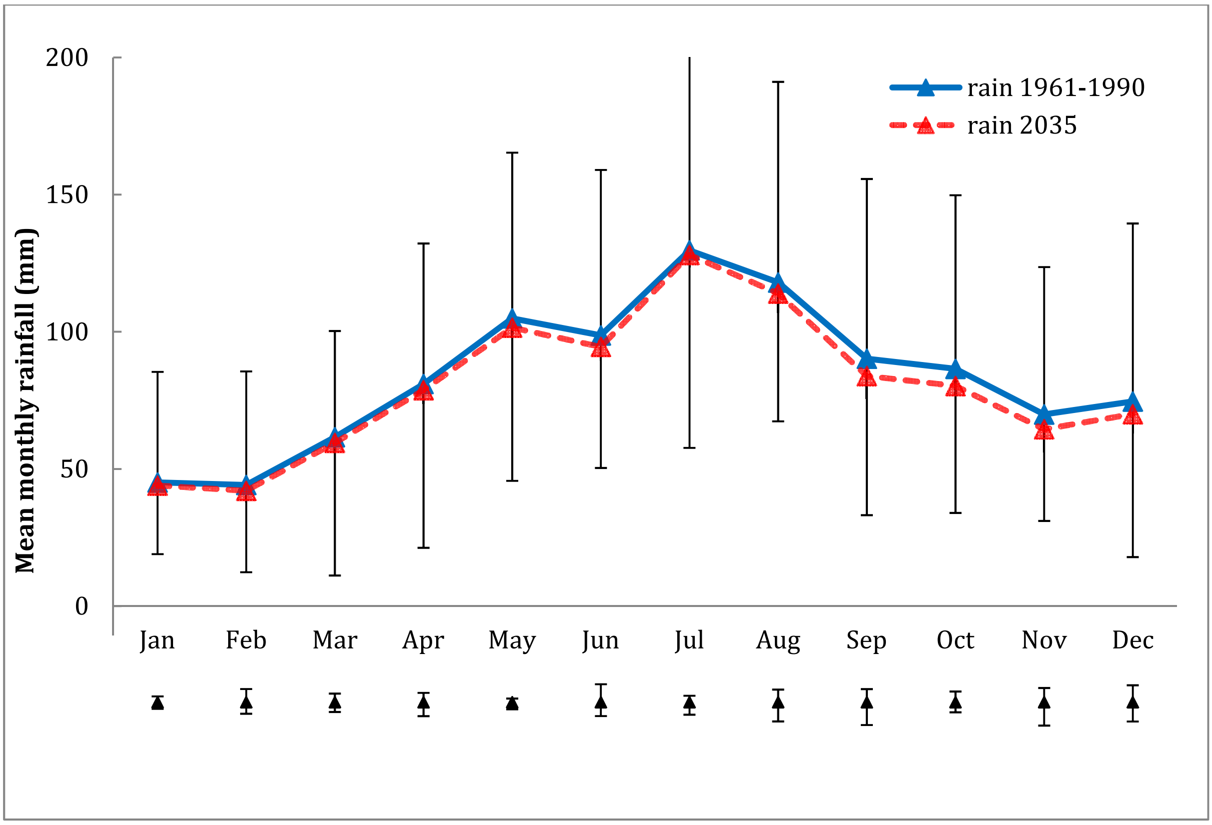


Figure 21. The mean monthly rainfall is shown for the Devonport region. The average for the 1961-1990 period is shown in blue, together with 10th and 90th percentiles, as indicated by the bottom and top bars, respectively. The projected mean monthly rainfall for 2035 is shown in red. The error bars at the bottom indicate the variation between the three model projections.

2.7.7.2 Devonport: Potential impacts on vegetable production – a discussion starter

Growing conditions

- Devonport appears to be the region least affected by projected changes in the climate. Small increases in mean monthly maximum and minimum temperatures add to what is already a mild climate.

Water availability

- Devonport region is dependent on winter river extraction into storage and direct summer river extraction during the months of December to April. The projected reductions in spring rainfall will increase the requirement for irrigation.

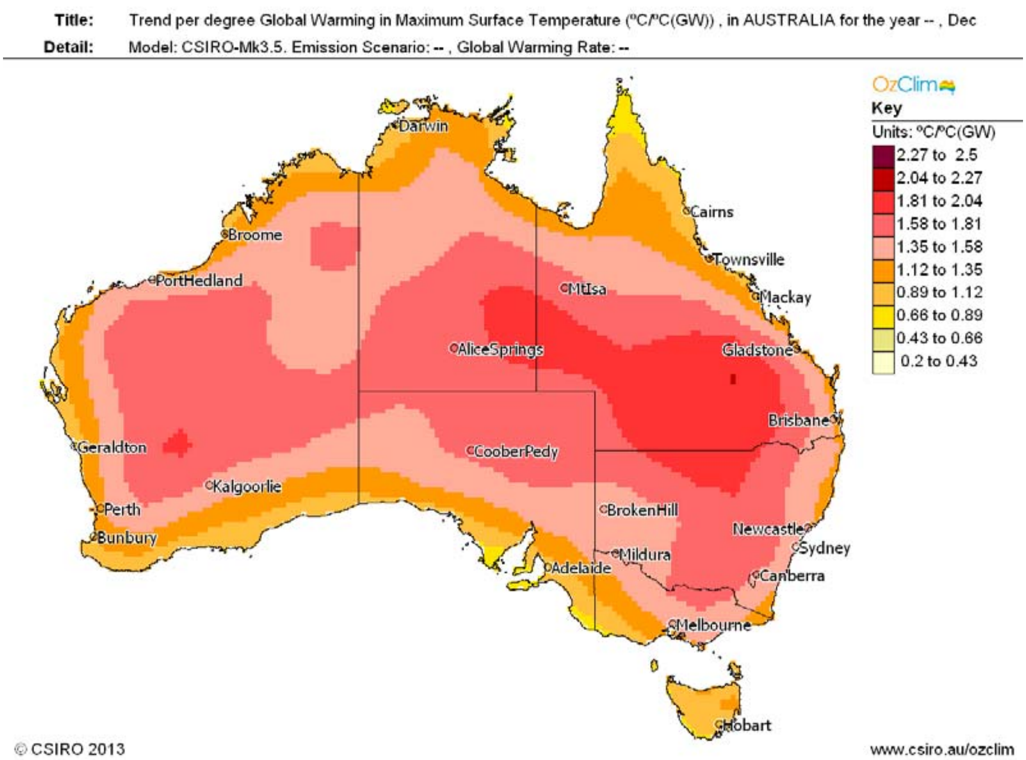
2.8 Graphical representations of expected regional changes in temperature in response to an increase of 1°C in average temperatures.

The following representations are the expected changes in monthly maximum temperatures for every 1°C in overall average temperature change over the year. Some areas will heat up more the average and other areas will heat up less than average. These figures are intended to give you an idea of how these changes in maximum temperatures are expected to occur around Australia. A value greater that 1 means the area will heat up more rapidly than the average and a value less than 1 means the area will heat up more slowly than the average.

The scenarios were generated using OzClim[31] using the CSIRO Mk3.5 global climate model which has a moderate climate sensitivity.

2.8.1 Summer: Predicted average monthly maximum temperature changes per °C of average warming

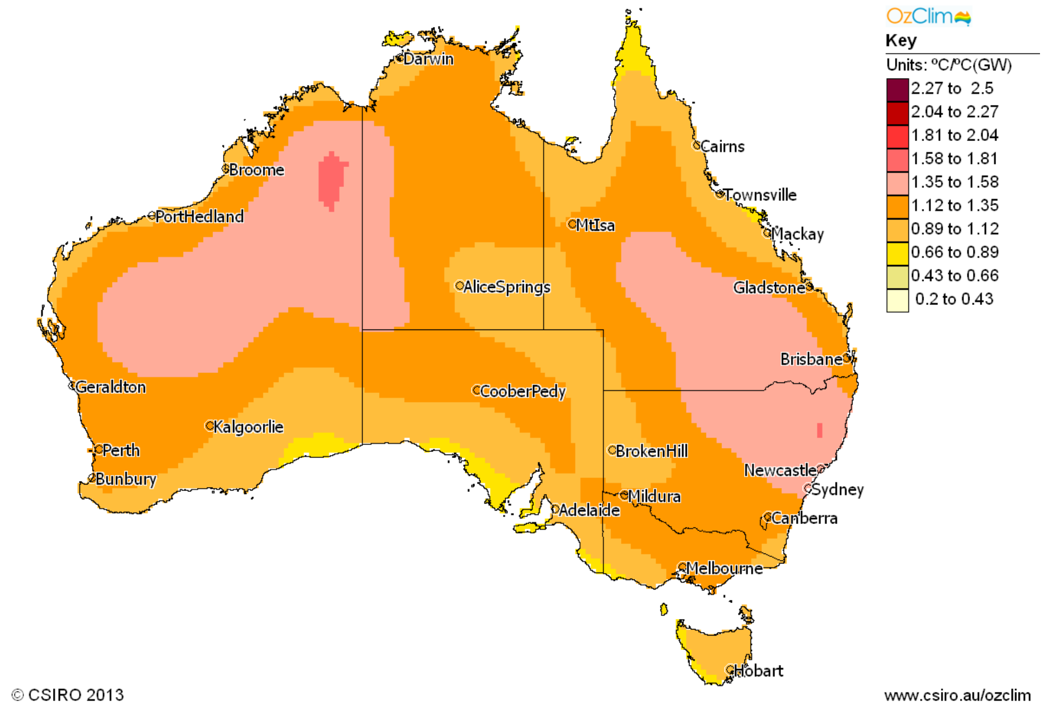
December



31 http://www.csiro.au/ozclim

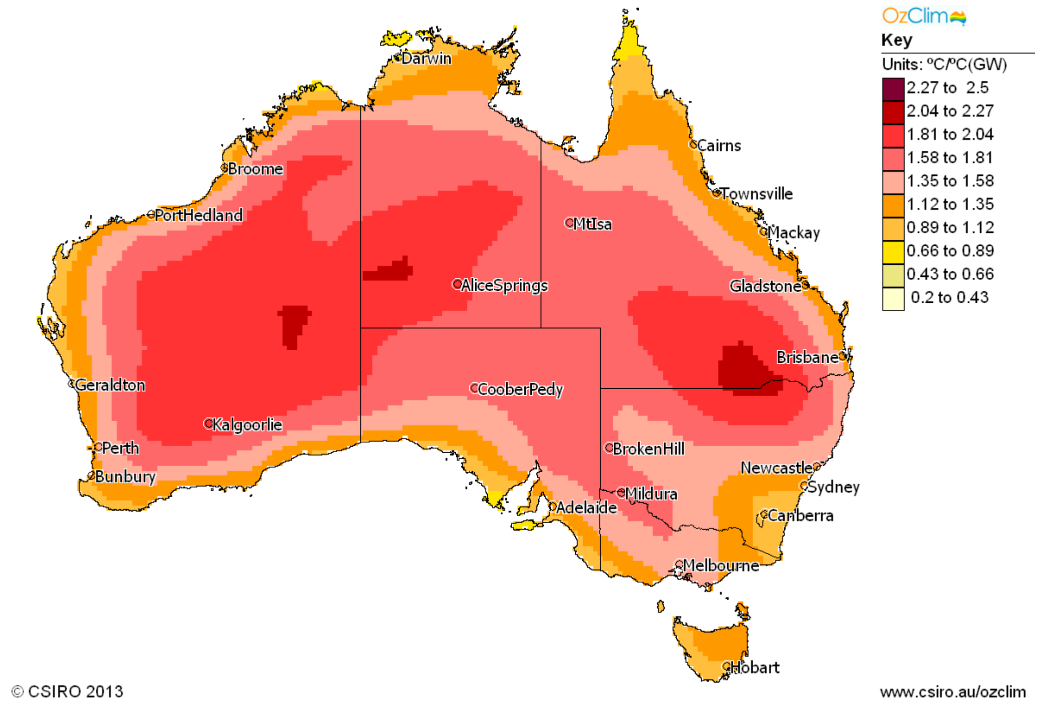
January

Title: Trend per degree Global Warming in Maximum Surface Temperature (ºC/ºC(GW)) , in AUSTRALIA for the year -- , Jan
Detail: Model: CSIRO-Mk3.5. Emission Scenario: -- , Global Warming Rate: --



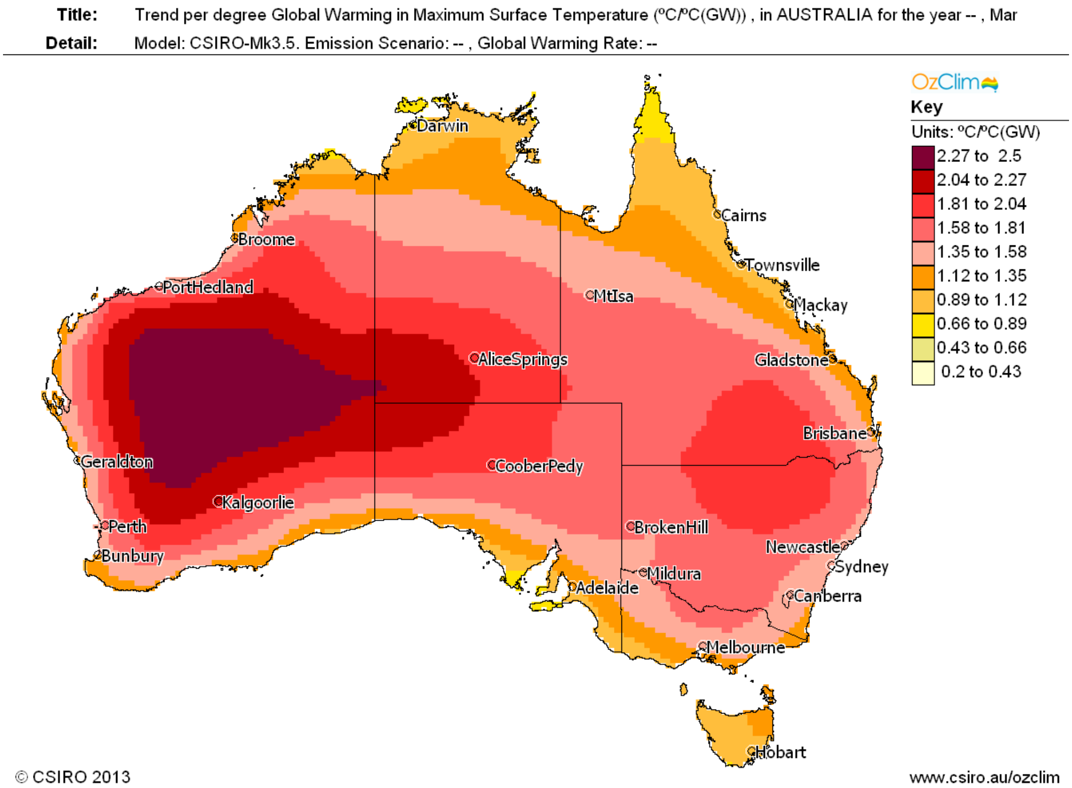
February

Title: Trend per degree Global Warming in Maximum Surface Temperature (ºC/ºC(GW)) , in AUSTRALIA for the year -- , Feb
Detail: Model: CSIRO-Mk3.5. Emission Scenario: -- , Global Warming Rate: --

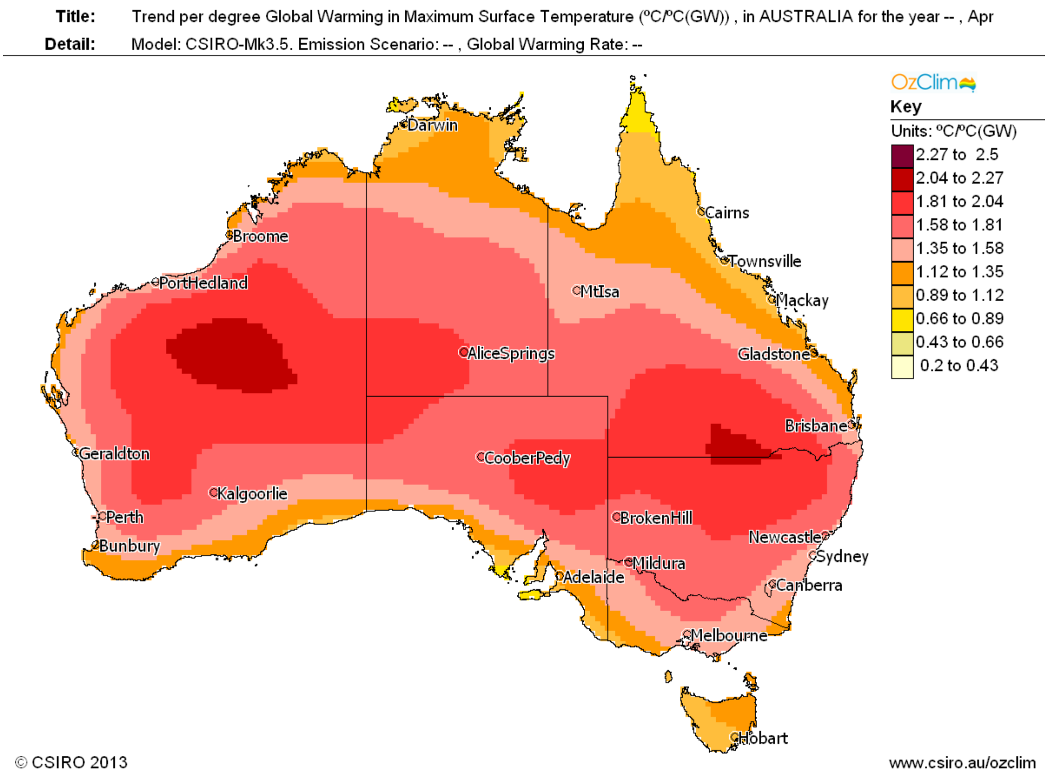


2.8.2 *Autumn: Predicted average monthly maximum temperature changes per °C of average warming*

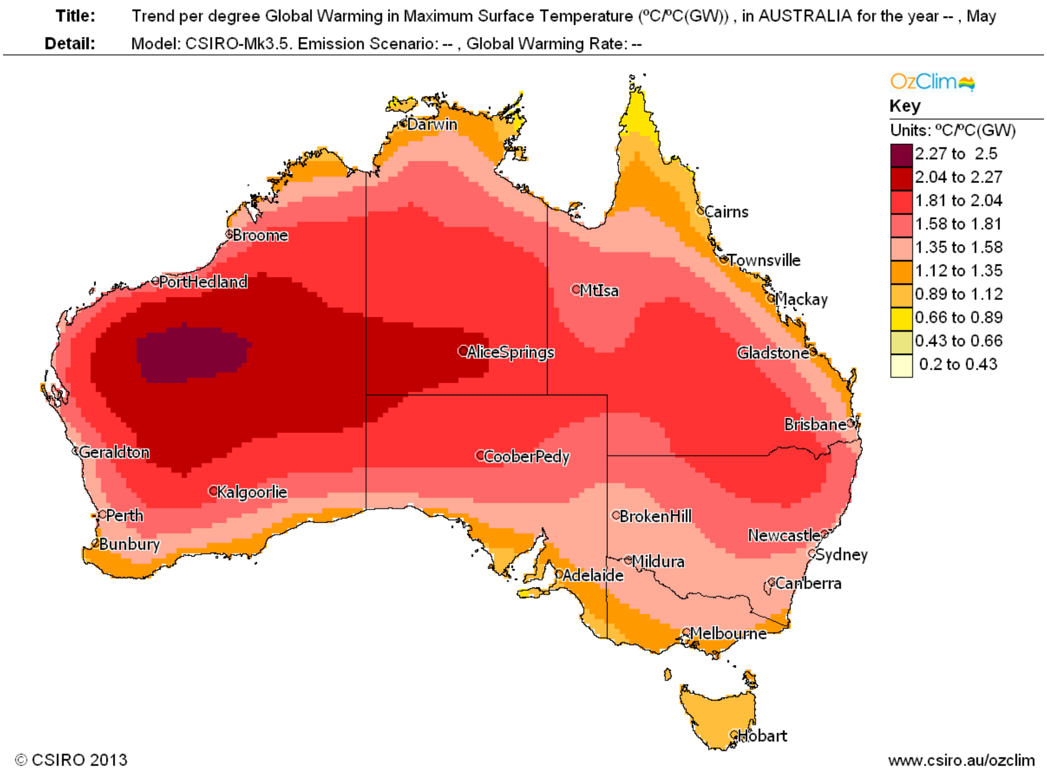
March



April

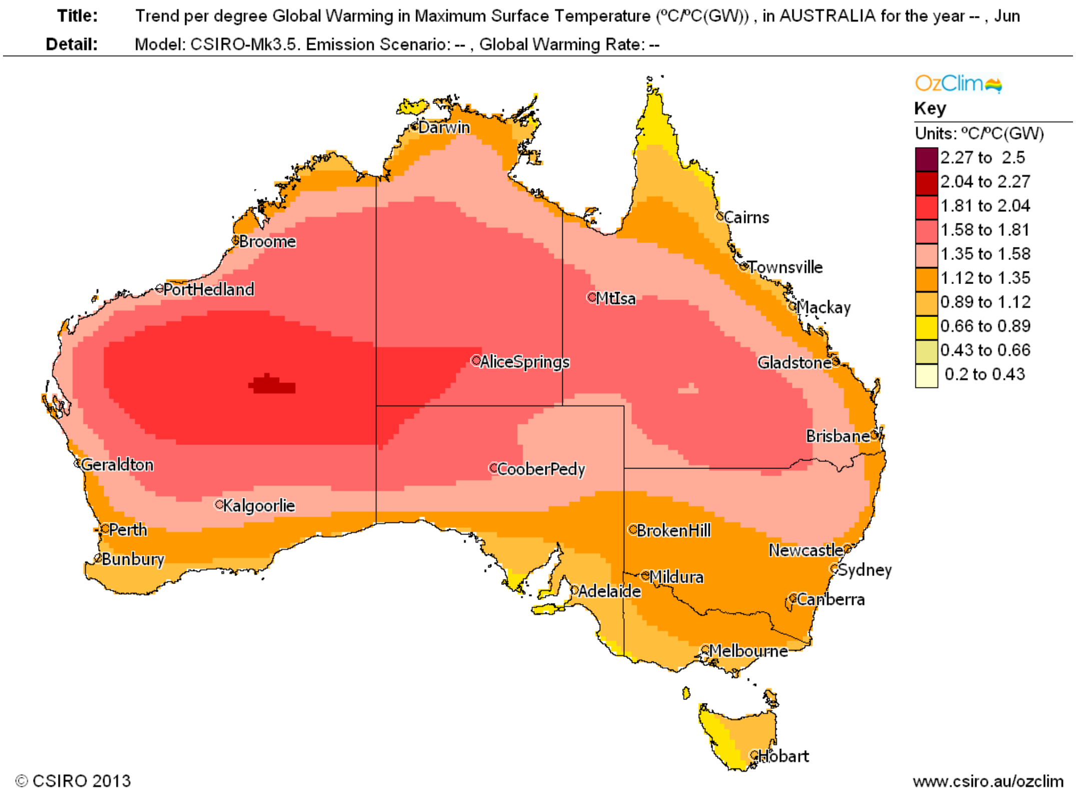


May



2.8.3 *Winter: Predicted average monthly maximum temperature changes per °C of average warming*

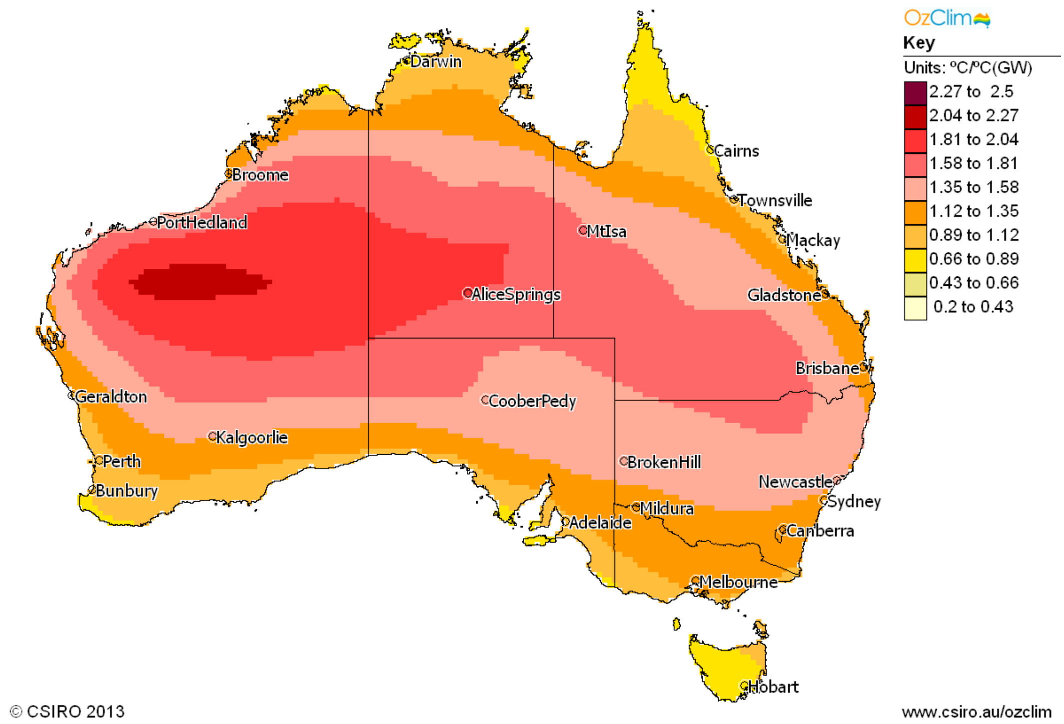
June



July

Title: Trend per degree Global Warming in Maximum Surface Temperature (ºC/ºC(GW)) , in AUSTRALIA for the year -- , Jul

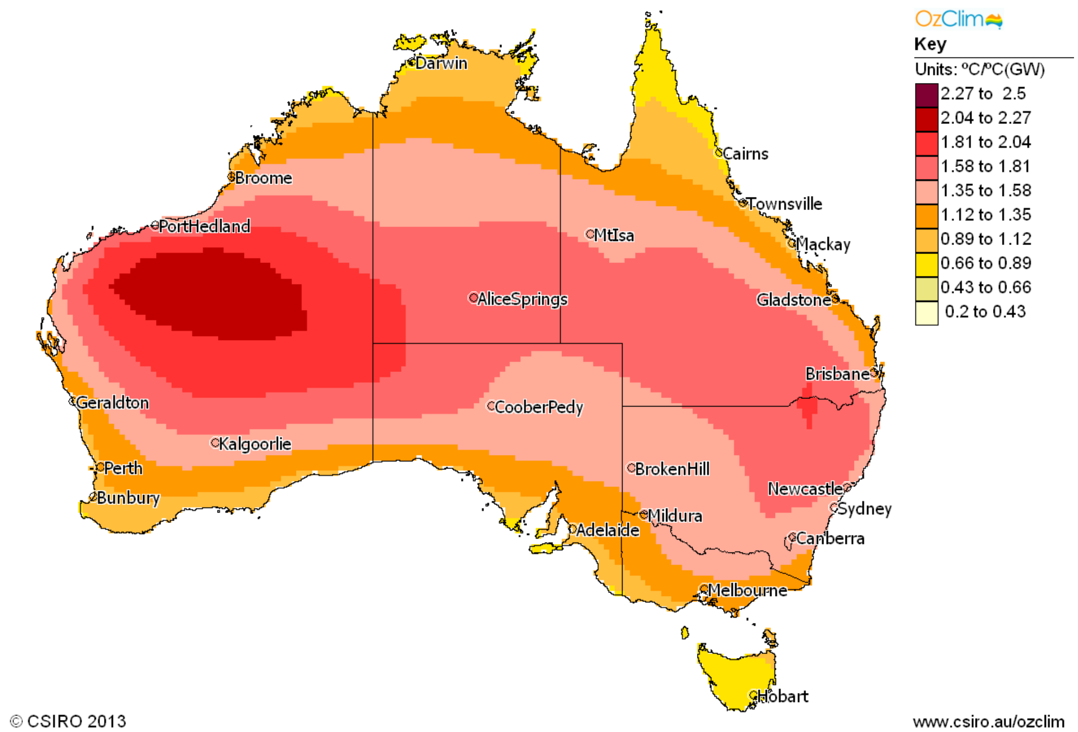
Detail: Model: CSIRO-Mk3.5. Emission Scenario: -- , Global Warming Rate: --



August

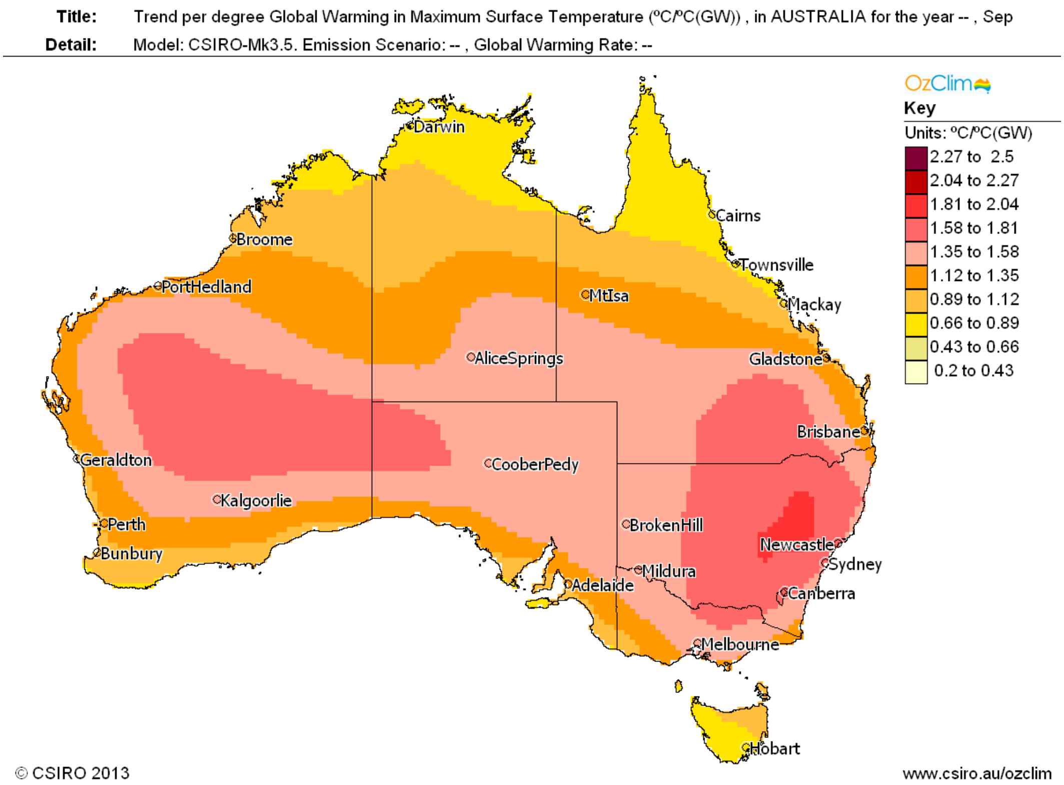
Title: Trend per degree Global Warming in Maximum Surface Temperature (ºC/ºC(GW)) , in AUSTRALIA for the year -- , Aug

Detail: Model: CSIRO-Mk3.5. Emission Scenario: -- , Global Warming Rate: --

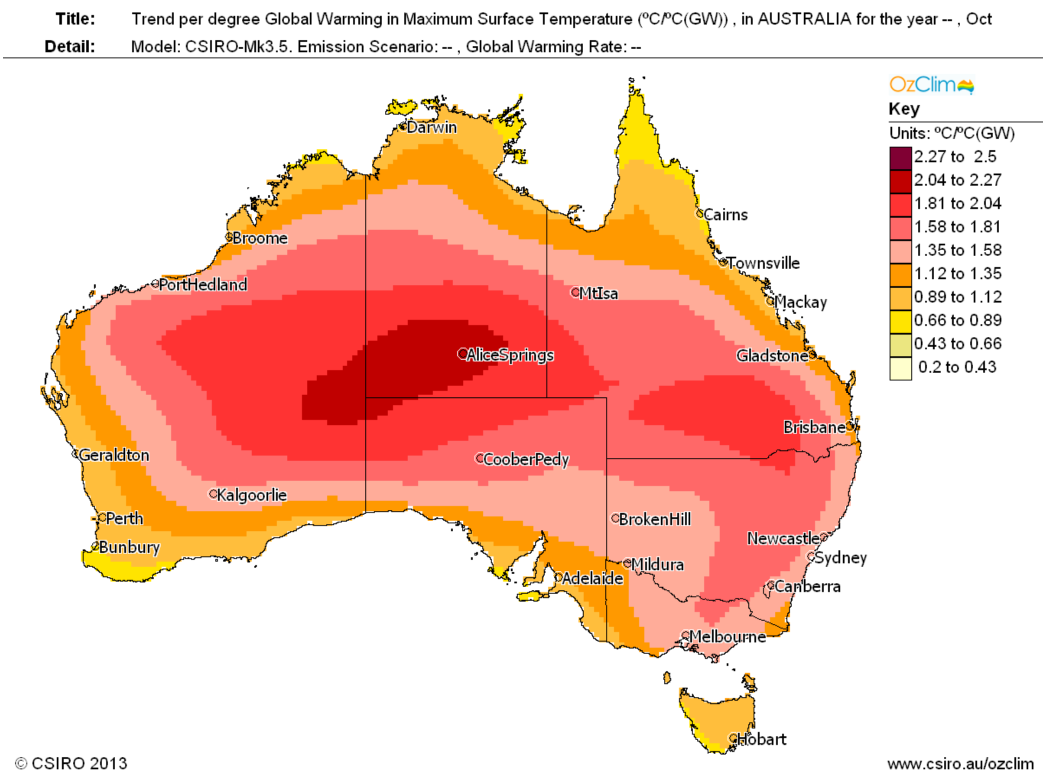


2.8.4 *Spring: Predicted average monthly maximum temperature changes per ^{o}C of average warming*

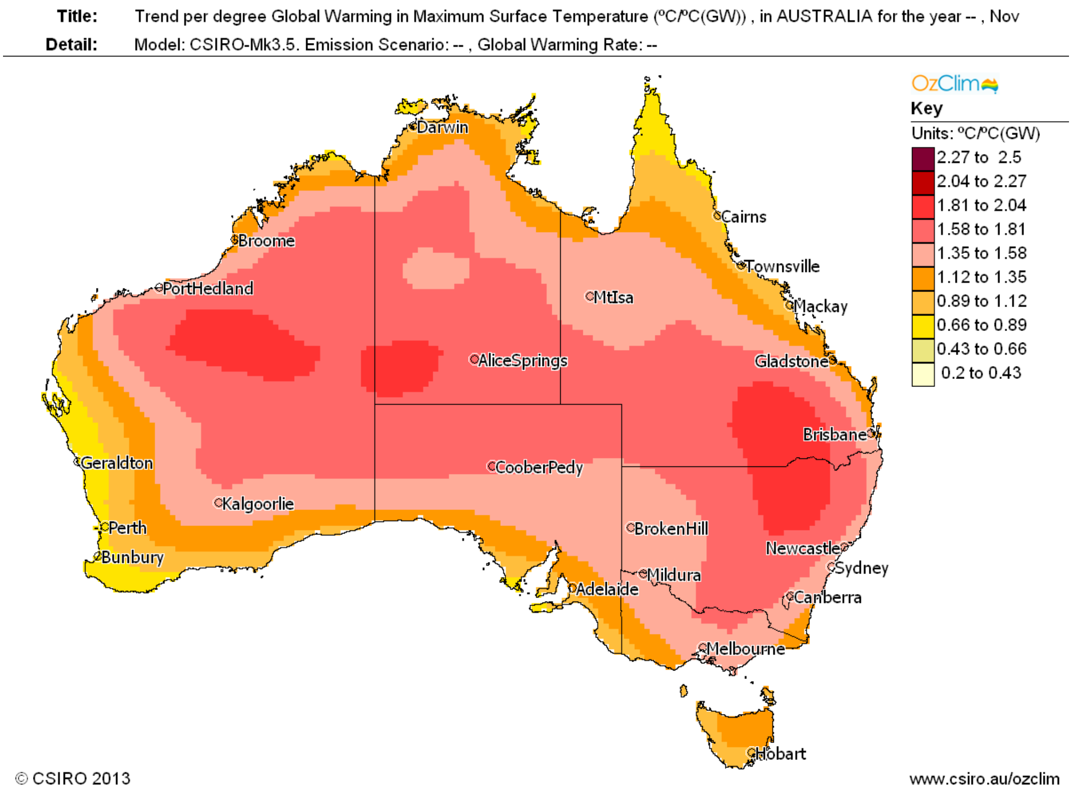
September



October



November



2.9 Predictions of the impact of increased climate variability and change on eight vegetable crops

The following section provides a summary of the expected impacts that changing temperatures will have on a selection of eight vegetable crops. The information for these predictions comes from cited reference material, comments from seed companies and from personal consultations[32].

[32] Mike Titley, pers comm.

2.9.1 Carrots

Carrots are a major vegetable crop in Australia, ranking 5th in value of production and with a strong export focus. There have been significant genetic improvements in carrots in recent years, predominately the move to F1 hybrids which are much less sensitive to premature bolting at low temperature.

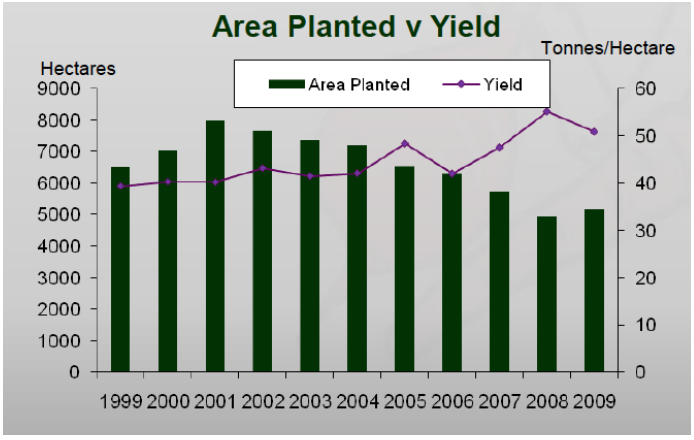


Figure 22. Area planted and average yields[33]

Temperatures	Air temperature (°C)	Expected yields (t/ha)	Yield impacts (%)	Impacts of exceeding temperature thresholds
Optimal range	15 - 18	55	0	
Upper threshold	27 - 30	38	-30	Abnormal root shape, reduced beta-carotene levels. Higher day temperatures are okay provided night temperature drops to 15-16°C. New F1 hybrid varieties mean carrots can be grown in warmer climates, e.g. year-round production in coastal WA.
Lower threshold	7	45	-20	Bolting (premature flowering and seed development). Minimum applies to F1 hybrids.

Scope to extend the temperature thresholds through breeding

- Breeding for low temperature tolerance (high vernalisation temperature)[34].
- Breeding for high beta-carotene and quality.

33 AusVeg crop spotlights www.ausveg.com.au
34 Simon, P. and Peterson, C. (1980) Interaction of genotype, soil, and climate in carrot flavor. Hortscience 15:421.

2.9.2 Lettuce (Cos, Iceberg, fancy)

The lettuce industry in Australia is our 6th largest vegetable industry by value. It is made up of field production of Iceberg and Cos head lettuce, with a significant proportion of Iceberg lettuce grown for processing. Lettuce also makes up one of the top three baby-leaf vegetables with spinach and rocket, and there is a significant market in “fancy” type lettuces, many of which are gown using NFT hydroponic systems with some form of protected cropping.

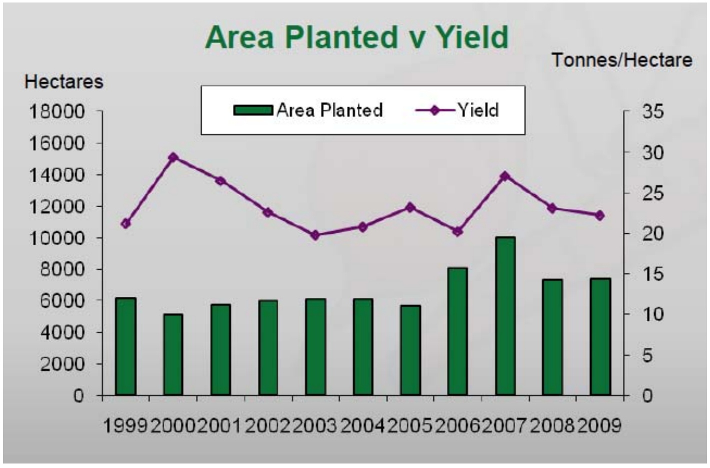


Figure 23. Area planted and average yields[35]

Temperatures	Air temperature (°C)	Expected yields (t/ha)	Yield impacts (%)	Impacts of exceeding temperature thresholds
Optimal range	12 - 21	30	0	
Night temperature	15 - 16	-	-	Higher night temperatures result in tipburn especially with high humidity.
Upper threshold	32	15	-50	Bolting, tipburn, low head weights, pale colour, bitterness. Thermo dormancy in lettuce seed above 25°C. Overcome using seedlings or priming in 1% K_3PO_4 or water.
Lower threshold	0	20	-35	Anthracnose, external frost damage, russeting, external cracking. Lettuce can tolerate low temperature, (including below 0°C for short periods). Low temperature extends the growing period up to 150 days.

Scope to extend the temperature thresholds through breeding

- Monsanto/Seminis are breeding summer vanguard Iceberg lettuce for heat tolerance in the tropics and sub-tropics[36]
- There is some breeding underway to improve varieties for colder regions in southern Australia and New Zealand[37]

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35 AusVeg crop spotlights www.ausveg.com.au
36 Monsanto/Seminis

2.9.3 Capsicums

Capsicum is a major Australian crop, with about 7% grown under protected cropping and the remainder produced in the open field. The production areas have been declining in recent years, however capsicums remain a major crop for the Australian vegetable industry.

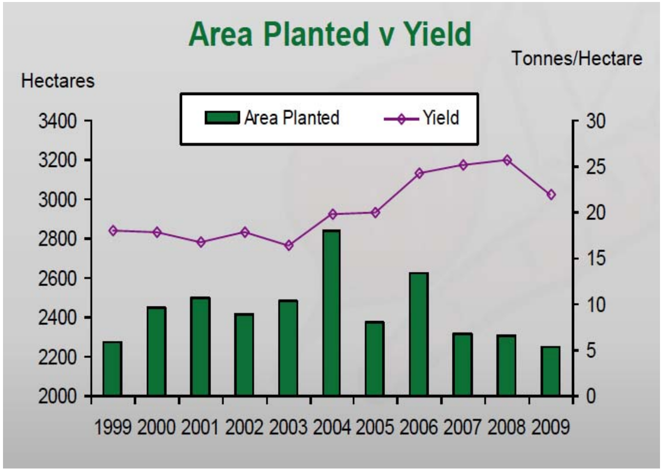

Figure 24. Area planted and average yields[38]

The temperature extremes can occur due to long-term average temperatures or by increased variability resulting in short-term heatwaves or cold periods.

Temperatures	Air temperature (°C)	Expected yields (t/ha)	Yield impacts (%)	Impacts of exceeding temperature thresholds
Optimal range	20 - 25	30	0	
Upper threshold	32	24	-20	Reduced pollen viability and reduced pollen release, both leading to reduced fruit set and yield. Sunburn.
Lower threshold	8-10	20	-35	Abnormal and misshapen fruit. Low temperatures can be addressed by growing under protected cropping.

Scope to extend the temperature thresholds through breeding

- Breeding for high temperature tolerance is difficult because the impacts are on fundamental physiological processes affecting pollen viability and release, however AVRDC[39] is breeding varieties with a tolerance of up to 32°C.
- Breeding for tolerance to low temperatures is more achievable, with the capacity to produce varieties with tolerance to night temperatures of 8-10°C[40].

37 Enza Zaden
38 AusVeg crop spotlights www.ausveg.com.au
39 AVRDC: The World Vegetable Centre, Taiwan
40 Y. Elkind et al, (2008) breeding of blocky type pepper varieties adapted for production in greenhouses and net houses in mild winter regions. ACTA Hort 797.

2.9.4 Broccoli

Broccoli is one of the major vegetable crops in Australia, ranking 9th in value of production. The main production areas are in Victoria and SE Queensland. The production trend for broccoli has been a decline in production since 2005, but remaining steady since 2007 at about 45,000 tonnes per year. The crop is highly temperature-sensitive but there are a large number of varieties that have been bred for production slots.

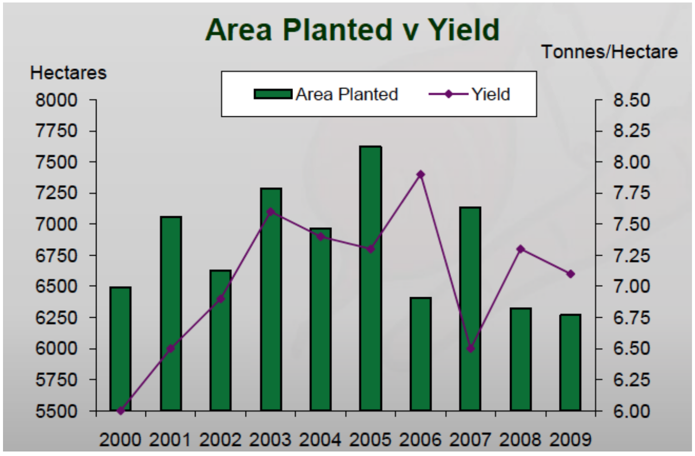

Figure 25. Area planted and average yields[41]

Temperatures	Air temperature (°C)	Expected yields (t/ha)	Yield impacts (%)	Impacts of exceeding temperature thresholds
Optimal range	21 - 22	7.5	0	Early maturing, hot weather types
	17 - 18	7.5	0	Transition varieties for spring and autumn
	4 - 5	7.5	0	Cool season varieties
Upper threshold	30 - 32	4	-45	Okay as long as nights get down to 15°C. E.g. Bathurst, Stanthorpe, Cooma at 700-1000m. Problems are: blindness, brown head, bracting in the head, catseye, uneven floret size, uneven cluster development, loose clusters. Often varieties that will grow in hot weather do not have the best quality.
Lower threshold	4	5.5	-25	Water soaked area, purple (anthocyanin) colours and yellow colours in the head (undesirable).

Scope to extend the temperature thresholds through breeding

- Japanese seed company, Sakata Vegetable Seeds, dominates broccoli breeding: see temperature-tolerance range available in the table above.
- Breeders will have to overcome the anthocyanin development at low temperature.

41 AusVeg crop spotlights www.ausveg.com.au

2.9.5 Sweet corn (processing)

Sweet corn is a major warm-season vegetable crop in Australia, with an annual value of production of about $80M[42]. Sweet corn is a direct-seeded crop and a monocot (grass), unlike most other vegetables, which are dicots (broadleaf plants).

Temperatures	**Air temperature (°C)**	**Expected yields (t/ha)**	**Yield impacts (%)**	**Impacts of exceeding temperature thresholds**
Optimal range	24 - 30	17	0	
Upper threshold	32	12	-30	Pollen blast. Prolonged temperature above 32 °C can reduce pollen germination to zero, resulting in no kernels developing on the cob[43].
Lower threshold	12	9	-50	Poor germination, and low percentage emergence, poor phosphorus uptake.

Scope to extend the temperature thresholds through breeding

- The greatest scope is to improve seed quality of the super sweet varieties in coping with cold, wet soil in spring.
- Traditionally sweet corn is not planted until the soil temperature reaches 15°C. The challenge would be to breed varieties that will germinate at temperatures down to 12°C.
- Breeding for heat tolerance would also be useful, however to the authors' knowledge, there are no breeding programs currently addressing this issue.

[42] AusVeg
[43] Herrico and Johnson (1980)

2.9.6 Beans

French beans and runner beans rank equally with broccoli as the 10th largest vegetable crop by value. Most of the production is in Queensland (winter) and Tasmania (summer).

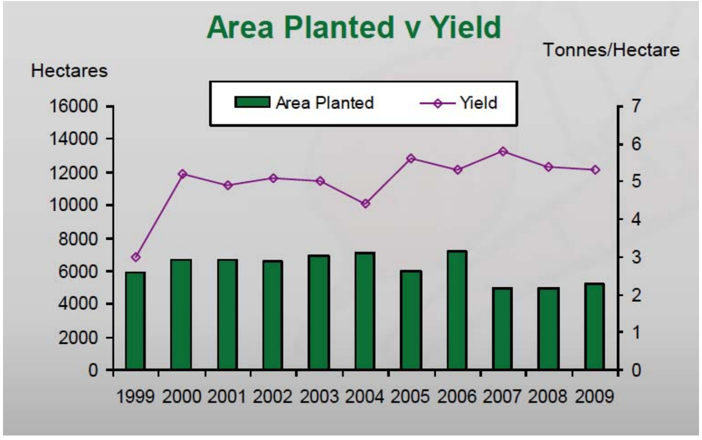

Figure 26. Area planted and average yields[44]

Temperatures	Air temperature (°C)	Expected yields (t/ha)	Yield impacts (%)	Impacts of exceeding temperature thresholds
Optimal range	15 - 21	6	0	
Upper threshold	28	4	-35	Above 28°C, pollen viability is decreased resulting in reduced yield and abscission of flower buds. Increased fibre in pods.
Lower threshold	10	3	-50	Poor root system development. Reduced photosynthesis and yield.

Scope to extend the temperature thresholds through breeding

- There is scope to breed for improved drought tolerance with better root systems.
- In the tropics, French beans (*Phaseolus vulgaris*) can be replaced by snake beans (*Vigna unguiculata*) which are more tolerant to high temperature.
- There has been some breeding for high temperature tolerance[45] and low temperature tolerance by Matt Silbernagal (USDA-ARS) and Tsonev[46].
- Breeding for temperature tolerance in beans should be considered as a long-term project.

44 AusVeg crop spotlights www.ausveg.com.au
45 Suzuki, K. et al, (2001) Decrease of Pollen Sustainability of Green Bean at High Temperatures and Relationship to Heat Tolerance. J. Amer. Soc Hort. Sc. 126(5):571-4.
46 Tsonev, T. et al. (2002) Low Temperature Enhances Photosynthetic Down-regulation in French Bean (Phaseolus vulgaris L.) Plants Annals of Botany, 91:343-52.

2.9.7 Cauliflower

Cauliflower is one of the smaller vegetable crops grown in Australia, with a total production value of $49.8M in 2009. It ranks 18th in terms of value of production across the vegetable industry. It is a cool-season crop grown mainly in Victoria and Queensland, with smaller amounts grown in other States.

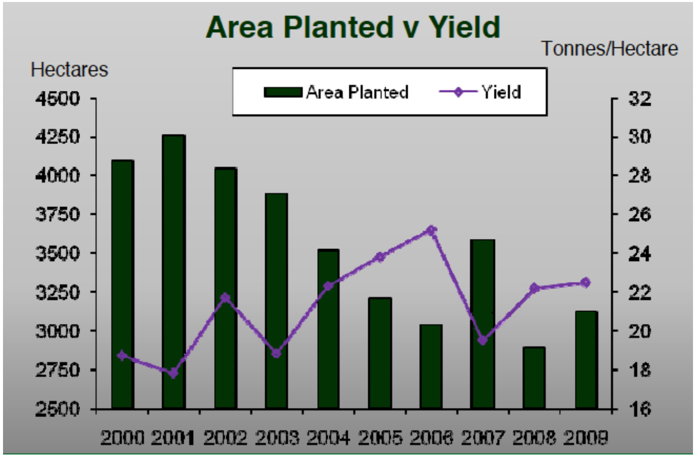

Figure 27. Area planted and average yields[47]

Temperatures	Air temperature (°C)	Expected yields (t/ha)	Yield impacts (%)	Impacts of exceeding temperature thresholds
Optimal range	15 - 18	23	0	
Upper threshold	32	13	-45	Bolting, yellow curd colour, uneven floret development.
Lower threshold	0	20	-15	Not really a problem. There are many varieties with cold tolerance that can be grown over winter[48]. Overwintering types available for spring harvest.

Scope to extend the temperature thresholds through breeding

- Tropical and sub-tropical genetics is available from India for early-maturing tropical cauliflower which produces white heads in 56-63 days, and is used by commercial seed companies in Asia, e.g. EastWest Seeds.
- Long-day overwintering types are available for Northern Europe[49].

47 AusVeg crop spotlights www.ausveg.com.au
48 Nickerson-Zwaan have 230 winter varieties
49 Tozer Seeds, UK

2.9.8 Beetroot (processing)

Beetroot is a minor crop in Australia and is included as an example of a processing crop. The main production is in SE Queensland and central NSW. Annual value of production is valued at about $10-14M, over recent years[50]. Hybrid beetroot has extended the traditional growing season by replacing the industry-standard open pollinated variety: *Imperial Dark Red Detroit*.

Temperatures	**Air temperature (°C)**	**Expected yields (t/ha)**	**Yield impacts (%)**	**Impacts of exceeding temperature thresholds**
Optimal range	18 - 25	35	0	
Upper threshold	27	25	-30	Bolting, poor colour and shape of the root – zoning occurs which is light and dark rings in the root, and these are not desirable for processing. Emergence problems caused by infection with Damping off fungi at high soil temperature.
Lower threshold	5	30	-15	Nutrient disorders: hollow heart caused by calcium and boron deficiency exacerbated at low temperature, phosphorus deficiency.

Scope to extend the temperature thresholds through breeding

- Breeding to extend the high temperature cut-off of 27°C would be the highest priority, however the authors' are not aware of any breeding programs currently addressing this issue.

[50] AusVeg

2.10 Regional impacts on vegetable crops in response to daily average temperature increases up to 4°C

This section describes predicted impacts on crops with temperature increases of:

- 1°C
- 2°C
- 3°C
- 4°C
- Five consecutive days above 35°C.

The impacts on the crops commonly grown in each of the regions studied in this report are described.

These descriptions relate to the temperatures that the crops experience and ***not to changes in monthly average temperatures***. An increase of 1°C in monthly average temperature can easily mean increases of 4°C or more on particular days. Refer to the Manjimup case study for an example of how this can occur (section 2.6.3).

2.10.1.1 Manjimup

Crops	+ 1°C average temp	+ 2°C average temp	+ 3°C average temp	+ 4°C average temp	5 days over 35°C
Lettuce Traditionally harvest Dec-May; season will extend.	Days to harvest quicker by 2-3 days	Need to change varieties summer types increased tipburn	May require protective shading during summer, transition period longer	Avoid summer lettuce, transition & winter lettuce area	Quality and yield decline
Baby leaf lettuce, spinach, rocket Harvest Oct-June	Days to harvest quicker 2-3 days	Days to harvest quicker 3-5 days , change varieties ,extended harvest period	Days to harvest quicker 6-7 days, new varieties, all year round production	Days to harvest quicker 8-9 days, new varieties, all year round production	Germination problems in summer if >35° Fringe 'burn' on leaf quality
Capsicums Not currently a suitable area, with increased temperature could be grown in summer	Harvesting possible Jan-Mar	Harvesting possible Jan-Apr	Harvesting possible Mid Dec-May	Harvesting possible Dec-late May	Sunscald and blossom end rot
Broccoli & cauliflower Traditionally all-year-round harvesting	Increased temperatures resulted in earlier maturity	Change of variety mix as winter's warmer and summer's hotter	Less cool season varieties in schedule	Increased quality problems, 'buttoning', pre-mature heading tipburn, hollow stem and increased white blister. Harvest window reduced to June-Oct	Quality decreases

2.10.1.2 Gatton

Crops	+ 1°C average temp	+ 2°C average temp	+ 3°C average temp	+ 4°C average temp	5 days over 35°C
Lettuce Traditionally May-October cool weather harvest	Days to harvest quicker by 2-3 day	Days to harvest quicker 3-4 days, change varieties	Days to harvest quicker 5-6 days, optimum harvest time contract June-Sep	Need transition varieties all season ,no winter types Optimum harvest time contracted further	Unlikely during winter period
Baby leaf lettuce, spinach, rocket Traditionally harvest Baby Leaf May-Oct	Days to harvest quicker 2-3 days	Days to harvest quicker 3-5 days , change varieties, extended harvest period	Days to harvest quicker 6-7 days, new varieties, all year round production	Days to harvest quicker 8-9 days, new varieties, all year round production	Germination problems in summer if >35° Fringe 'burn' on leaf quality
Capsicums Traditionally considered transition harvesting in spring & autumn	Earlier transplanting in winter as less frost damage & later harvesting in autumn	Harvest possible Nov & Dec/May & June	Harvest possible late Oct& Nov /late May & June	Harvest possible Oct& Nov /Late may-early July	Would affect late spring crops with sunscald & blossom end rot
Carrots Optimum harvest time months June-Dec	Yield increases and reduced time to harvest	Yield increases and reduced time to harvest, spring harvest ceasing in Nov	Harvest window mid June-Nov as temperatures rise	Harvest window July-mid Nov	Germination and establishment problems, increased soil borne pathogens
Broccoli & cauliflower Traditionally winter & early spring harvest	Earlier maturity	Change in variety mix	Less cool season varieties	Harvest window reduced to June-Oct	Quality & yield decreases
Beans Traditionally transition harvest in Nov-Dec/Apr-May	Harvest earlier in spring and later in autumn	Earlier planting in winter after last frost Heat in summer delays autumn crop	Restrict harvest to Oct/Nov & May/June	Restrict harvest late Sep/Oct & late May-early July	Causes huge flower drop and reduced pod set
Sweet Corn (processing) Traditionally harvest in	Harvest earlier in spring and later in	Earlier planting in winter after last frost	Restrict mid summer harvest in mid Jan-mid	Restrict harvest Jan-March or move	Causes pollen blast and affects tip fill in

Crops	+ 1°C average temp	+ 2°C average temp	+ 3°C average temp	+ 4°C average temp	5 days over 35°C
Nov-May	autumn	Heat in summer lower yield autumn crop	March or move to Eastern Darling Downs	production to Eastern Darling Downs	cobs stressed when temperatures > 35°C
Beetroot (processing) Traditionally harvested April-November) as cool season crop	Earlier maturity and increased yield	Commence harvesting May due to problems in establishment in the autumn heat	Commence harvesting mid May, higher yields during winter with increased winter temperatures	Commence harvesting late May and complete by mid October as the spring heats up	Germination problems Zoning (alternating light/dark bands in beets resulting downturn in quality

2.10.1.3 Hay

Crops	+ 1°C average temp	+ 2°C average temp	+ 3°C average temp	+ 4°C average temp	5 days over 35°C
Lettuce Traditionally May-October harvest using winter varieties	Days to harvest quicker by 3-4 days	Days to harvest quicker 5-7 days, change varieties	Days to harvest quicker 8-10 days, change varieties in mid winter	Commence season later, improved quality in id winter as less frosts, change varieties	Unlikely during winter harvest period
Baby leaf lettuce, spinach, rocket Not a traditional area for winter grown baby leaf	Days to harvest quicker by 3-4 days	Days to harvest quicker 5-7 days, change varieties	Days to harvest quicker 8-10 days, change varieties in mid winter	Commence season later, improved quality in id winter as less frosts, change varieties	Unlikely during winter harvest period
Broccoli & cauliflower Traditional harvest window May-Nov	Earlier maturity	Change in variety mix	Less cold season varieties	Harvest window reduced to June-Oct	Quality & yield decreases

2.10.1.4 Werribee

Crops	+ 1°C average temp	+ 2°C average temp	+ 3°C average temp	+ 4°C average temp	5 days over 35°C
Lettuce Traditionally Nov –May harvest period. Assuming quality of irrigation water improves or trickle used	Days to harvest quicker by 2-3 day	Need to change varieties summer types, increased tipburn	May require protective shading during summer, transition period longer	Avoid summer lettuce, becomes transition & winter lettuce area	Quality problems and yield decline
Broccoli & cauliflower Traditionally all-year-round harvesting	Earlier maturity	Change in variety mix	Less cold season varieties	Summer production may be less viable with increased white blister	Quality & yield decreases especially with White Blister

2.10.1.5 Murray Bridge

Crops	+ 1°C average temp	+ 2°C average temp	+ 3°C average temp	+ 4°C average temp	5 days over 35°C
Lettuce Traditionally Nov –May harvest period. Assuming quality of irrigation water improves or trickle used	Days to harvest quicker by 2-3 day	Need to change varieties summer types, increased tipburn	May require protective shading during summer, transition period longer	Avoid summer lettuce, becomes transition & winter lettuce area	Quality problems and yield decline
Capsicums Traditionally a glasshouse crop has relocated due to high cost town water	Less heating required during winter	Earlier production and cooling in summer	More production in winter & spring months, change varieties in warmer months	Shading and more cooling in summer months	Decline in fruit quality unless cooling and shading provided
Broccoli & cauliflower Traditionally all-year-round , drought reduced area now	Earlier maturity	Change in variety mix	Less cold season varieties	Summer production may be less viable with increased white blister	Quality & yield decreases with White Blister

2.10.1.6 Devonport

Crops	+ 1°C average temp	+ 2°C average temp	+ 3°C average temp	+ 4°C average temp	5 days over 35°C
Lettuce traditionally Nov-May harvest period	Days to harvest quicker by 2-3 days, higher yields	Days to harvest quicker by 4-5 days & higher yield	Change varieties, days to harvest quicker and extend harvest season	Change varieties to warmer season cultivars, growtht faster and extend harvest season.	N/A as temperatures won't reach > 35°C
Baby leaf lettuce, spinach, rocket Not considered a suitable area for summer/autumn baby leaf primarily in Hobart/Richmond/Cambridge region of Southern Tasmania	Days to harvest quicker 2-3 days	Days to harvest quicker 3-5 days, change varieties, extended harvest period	Days to harvest quicker 6-7 days, new varieties, all year round production	Days to harvest quicker 8-9 days, new varieties, all year round production	N/A as temperatures won't reach > 35°C
Carrots Traditionally optimum harvest period Jan – May	Harvest window Dec-June with higher yield and quality	Harvest window mid Nov-late June	Harvest window early Nov-early July	Harvest window late Oct-mid July	N/A as temperatures won't reach > 35°C
Broccoli & cauliflower Traditionally best harvest time Dec-June. With climate change possible harvest all-year-round	Earlier maturity & increase yield	Harvest period Nov-July	Harvest period Oct-August	all-year-round harvest possible with range of varieties	N/A as temperatures won't reach > 35°C
Beans Traditionally best harvest time Jan-Apr	Earlier maturity & increase yield	Harvest period mid Dec-mid May	Harvest period Dec-end May	Harvest period mid Nov-early June	N/A as temperatures won't reach > 35°C
Sweet Corn (processing) Traditionally best harvest time Feb-Apr	Earlier maturity & increase yield	Harvest period mid Jan-early May	Harvest period Jan-mid May	Harvest period late Dec-late may	N/A as temperatures won't reach > 35°C
Beetroot (processing) Currently all-year-round for fresh market	Earlier maturity & increase yield	Earlier maturity & increase yield	Earlier maturity & increase yield	Earlier maturity & increase yield	N/A as temperatures won't reach > 35°C

3 What are the impacts of increased climate variability on vegetable crops?

The impacts of climate change on vegetable crop growth and yield potential can be separated into direct effects of the higher CO_2 levels and indirect effects of climate change and variability including higher average temperatures, more frequent extreme weather events, droughts and flooding.

Direct effects of rising CO_2 levels on plants has been well studied on annual crop plants including vegetables. The main effects are:

- Increased growth due to more efficient photosynthesis at higher CO_2 levels.
- Reduced crop water use due to reduced evapotranspiration from leaves.
- More efficient use of nitrogen, i.e. less nitrogen required per unit of yield, and lower nitrogen concentration in plant tissue.

Indirect effects of climate change and increased climate variability on vegetable crops are predicted to be:

- Impacts of higher average temperatures.
- More extreme weather events including droughts, flooding and heatwaves.
- Increase in frost incidence.
- Changes in pest and disease impacts.
- Changes in weed impacts.

3.1 Direct effects

3.1.1 Crop growth and yield

The yield or growth rate of most vegetable crops is likely to increase as atmospheric CO_2 levels rise. This effect is well known in the glasshouse industry where CO_2 enrichment has been practiced for many years for crops such as tomatoes, cucumbers, capsicums and leafy vegetables, and results in more efficient photosynthesis and improved growth. The impact can be dramatic and growth-rate increases in the range of 20-50% can be expected if atmospheric CO_2 levels reach 500 ppm[51].

The current level of CO_2 is about 395 ppm and is increasing at a rate of about 2 ppm per year, and unless global abatement measures have a significant impact we can expect global atmospheric CO_2 levels to be about 435 ppm by 2035[52] .

[51] 24. Rogers, G. S., Milham, P. J., Gillings, M., and Conroy, J. (1996). Sink strength may be the key to growth and nitrogen responses in N-deficient wheat at elevated CO2. Australian Journal of Plant Physiology 23, 253-264

[52] Claugh, H. (2102) Climate change : science and solutions for Australia

At these levels of CO_2 we can expect significant effects on crop yield or growth rate. For example, capsicum yields were increased by 46% when grown at 450 ppm CO_2 compared to 360 ppm, and more modest increases have been observed for other crops such as eggplant (24%) and tomatoes (31%)[53].

These yield increases occur mainly because photosynthesis works more efficiently and respiration is reduced at higher CO_2 levels resulting in more photosynthate being available for growth and crop yields[54].

In perennial species such as fruit trees and forests there is an acclimation of this CO_2 fertilisation effect which diminishes its impact over time.

In practice however, observations on vegetable yields to date have been that observed yield increases are below potential gains. Yield is a complex phenotypic trait determined by the interactions of a genotype with the environment. Selection of promising varieties and characterisation of response mechanisms will only be effective if crop improvement and systems biology approaches are closely linked to on-farm production environments within major growing regions. Free air CO_2 enrichment (FACE) experiments can provide a platform on which to better understand the mechanisms that underlie differences in productivity under elevated CO_2[55].

3.1.2 Crop water requirements

In most plants, elevated CO_2 reduces water use or transpiration because the higher CO_2 level causes the pores in the leaves, or the stomata, to partially close[56]. This effect can be significant and can reduce the plant water requirement, e.g. a free to air (FACE) CO_2 study on wheat was able to show a 19% increase in water-use efficiency at elevated CO_2[57]. This may be relevant to vegetable crop production in a changing climate because one of the expected effects of climate change are more droughts. The higher CO_2 levels may have a compensatory effect by reducing water availability but also reducing the crop water requirement.

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53 Nederhoff, E. M. and J. G. Vegter (1994). "Photosynthesis of stands of tomato, cucumber and sweet pepper measured in greenhouses under various CO 2-concentrations." Annals of Botany 73(4): 353-361.
54 Bowes, G. (1991). "Growth at elevated CO 2: photosynthetic responses mediated through Rubisco." Plant, Cell and Environment 14(8): 795-806.
55 Ziska, L. H., J. A. Bunce, et al. (2012). "Food security and climate change: on the potential to adapt global crop production by active selection to rising atmospheric carbon dioxide." Proceedings of the Royal Society of London. Series B, Biological Sciences 279(1745): 4097-4105
56 Rogers, H. H. and R. C. Dahlman (1993). "Crop responses to CO 2 enrichment." Vegetatio 104-105: 117-131.
57 Wang, M., Y. Sun, et al. (2009). "Energy balance and water use efficiency at wheat canopy under free-air CO 2 enrichment." Zhongguo Shengtai Nongye Xuebao / Chinese Journal of Eco-Agriculture 17(2): 266-272.

The practical reality, however, is that in Australia virtually all vegetable crops are irrigated, and even though the price of water for irrigation rose to $1500 per ML in Australia in 2008 during a severe drought, vegetable growers are otherwise able to supply their crop water requirement without difficulty.

Electricity for pumping water is a major source of greenhouse gas emissions for the vegetable industry. If the crop water use can be reduced, through a combination of better crop water management and measuring soil moisture levels, it may be possible to reduce the water use requirement and therefore reduce the emissions and power costs in production because irrigation pumps can be run for a shorter time.

Physiological disorders such as tipburn in lettuce and brassica crops, blossom-end rot in tomato, capsicum and watermelon are sometimes associated with excessive transpiration, so the incidence of these disorders may be reduced under elevated CO_2 [58].

3.1.3 Crop nutrition

Nitrogen: There are two main effects of elevated CO_2 on the nitrogen nutrition and growth of vegetable crops. First, as CO_2 levels increase, the level of nitrogen in the tissue of plants decreases. This is due to more efficient use of nitrogen by plants grown at high CO_2 and means that less nitrogen is required to produce maximum yields than would be required at 1990 levels of CO_2. For example, in cucumbers[59], spinach and fenugreek[60] the N concentrations in the leaves were about 16% lower at high CO_2 compared to plants grown at ambient CO_2 levels.

The implication of this, if CO_2 levels continue to rise, vegetable crops will become more efficient in their use of nitrogen and therefore less will need to be applied. This may fit well with methodologies aimed at reducing N_2O emissions based on better nitrogen management as part of the Carbon Farming Initiative[61].

The other main impact of nitrogen is related to the growth and yield stimulation that can be expected at higher CO_2 levels. This response is highly dependent on the supply of nitrogen to the plants, as plants need adequate nitrogen to take advantage of the benefits of elevated CO_2[62].

58 Peet, M. M. and D. W. Wolfe (2000). Crop ecosystem responses to climatic change: vegetable crops.
59 Luomala, E. M., L. Sarkka, et al. (2008). Altered plant structure and greater yield of cucumber grown at elevated CO 2 in a semi-closed greenhouse. Acta Horticulturae. S. d. Pascale, G. Scarascia Mugnozza, A. Maggio and E. Schettini: 1339-1346.
60 Jain, V., M. Pal, et al. (2007). "Photosynthesis and nutrient composition of spinach and fenugreek grown under elevated carbon dioxide concentration." Biologia Plantarum 51(3): 559-562.
61 DAFF. (2013). "Carbon Farming Initiative." 2013, from http://www.climatechange.gov.au/cfi.
62 Rogers, G. S., P. J. Milham, et al. (1996). "Sink strength may be the key to growth and nitrogen responses in N-deficient wheat at elevated CO 2." Australian Journal of Plant Physiology 23(3): 253-264.

Other nutrients need to be present at optimal levels for plant growth and yield to take maximum advantage of elevated CO_2.

3.2 Indirect effects

3.2.1 Temperature

The direct effects of temperature are among the main issues expected to arise with a warmer and more variable climate. There will be three main impacts on temperature that will have an effect on vegetable crop production in the next 5 years, and the next 20 years. These expected impacts are:

- A rise in average monthly temperatures.
- An increase in the extremes of temperature (high and low).
- Increased risk of frost damage.

Changes in climate observed over the last 50 years will continue. For Australia, our best estimates are that by 2035, the temperature is projected to warm by about 1°C over Australia. Inland areas are likely to experience stronger warming of up to 1.8°C.

3.2.2 What impacts can be expected on crop scheduling and continuity of supply

There will be changes in the number days to harvest for particular crops in particular regions. Where crop prediction models have been produced and are used by industry, e.g. for lettuce, baby-leaf crops, and processing crops such as sweet corn, beans and peas, the models currently available will remain useful so long as the average temperatures used are increased according to the new averages that are likely to be experienced. Some market disruptions could also result in temporary shortages and/or oversupplies of products, and possible price changes for both consumers and producers.

3.2.3 Current and expected temperature thresholds for the common vegetable crops

Optimum temperature ranges for the main vegetable crops are shown in **Table 4**, and the ways in which these vegetables are expected to respond to temperature changes is shown in Table 5.

Table 4 Temperature ranges for vegetable crops

Crop	Growth and fruit production			
	Minimum	Lower optimum	Upper Optimum	Upper Maximum
	°C	°C	°C	°C
Artichokes	7	15	18	24
Babyleaf - chard	5	15	18	24
Babyleaf - rocket	5	16	24	32
Babyleaf - spinach	5	15	18	30
Beans	10	15	21	27
Beetroot	5	15	18	27
Broccoli	4	15	18	30 - 32
Brussels sprouts	5	15	18	24
Cabbage	7	15	18	24
Capsicums	18	20	25	32
Carrots	7	15	18	30
Cauliflower	0	15	18	32
Celery	7	15	18	24
Chillies	18	21	30	35
Cucumbers	15	18	24	32
Eggplant	18	21	30	35
Garlic	7	13	24	30
Herbs	7	15	18	24
Leeks	7	13	24	30
Lettuce - Cos	7	12	21	24
Lettuce - fancy and babyleaf	7	12	21	24
Lettuce - Iceberg	7	12	21	24
Parsnips	5	15	18	24
Peas	7	15	18	24
Pumpkin	10	18	24	32
Shallots	7	13	24	30
Silverbeet	5	15	18	24
Snow peas and Sugar snap peas	7	15	18	24
Swedes and Turnips	5	15	18	24
Sweet Corn	12	24	30	32
Tomato	18	18	24	29
Zucchini and butter squash	10	18	24	32

Source: Maynard and Hochmuth[63] with modifcations.

[63] Maynard, D. M. and G. J. Hochmuth (1997). Knott's Handbook for Vegetable Growers, Jhn Wiley and Sons.

Table 5. Impacts of frost and high temperature for a range of vegetable crops

Crop	Frost sensitivity	Specific frost-sensitive stage	High temperature sensitivity	Effects of prolonged hot weather
Broccoli	Tolerant	Emergence to 8 weeks	Very sensitive	Very poor quality heads, hollow stem, leafy heads, no heads, bracting.
Brussels sprouts	Tolerant	Emergence	Very sensitive	Cool season crop only
Cauliflower	Moderate tolerance	Emergence to 8 weeks	Very sensitive	Very poor quality curd, hollow stem, leafy heads, no heads, bracting.
Beans	Very sensitive	All stages affected by cool temperatures	Sensitive	Pollination problems, high fibre in pods
Carrots	Tolerant	Emergence to 8 weeks	Sensitive	Reduced yields & low beta carotene content (poor colour). Temperatures < 10°C or > 20°C
Celery	Moderate tolerance	Emergence to 8 weeks	Sensitive	Poor quality stems
Lettuce	Low tolerance	All stages	Sensitive	Bolting & small light heads, tipburn, bolting, loose, puffy heads. >24 °C day and 15 °C night, poor shelf life.
Babyleaf general: chard, Asian greens	Moderate tolerance	All stages	Sensitive	Low yield
Garlic	Tolerant	Emergence to 8 weeks	Sensitive	Cool season crop only
Kohlrabi	Tolerant	Emergence	Sensitive	Poor root quality
Leek	Tolerant	Emergence to 10 weeks	Sensitive	Cool season crop only
Parsnip	Tolerant	Emergence	Sensitive	Poor root quality
Peas	Tolerant	Flowering	Sensitive	Poor pollination
Babyleaf spinach	Moderate tolerance	All stages	Moderate	Low yield
Babyleaf rocket	Moderate tolerance	All stages	Moderate	Low yield
Turnip	Very tolerant	Emergence	Moderate	Poor root quality
Tomato	Very sensitive	All stages affected by cool temperatures.	Moderate	Fruit cracking, sunscald, poor fruit set above 27°C. Blossom-end rot when combined with water stress.

Crop	Frost sensitivity	Specific frost-sensitive stage	High temperature sensitivity	Effects of prolonged hot weather
Beetroot	Tolerant	Emergence	Moderate	Poor root quality
Cabbage	Moderate tolerance	Emergence to 8 weeks	Moderate	Loose, light heads
Chinese cabbage	Moderate tolerance	Emergence to 8 weeks	Moderate	Loose, light heads
Onion	Tolerant	Emergence to 10 weeks	Moderate	Bulb splitting
Snow peas	Moderate tolerance	Emergence to 6 weeks and flowering	Moderate	Reduced growth, fruit set
Asparagus	Very tolerant	Dormant in winter	Tolerant	High fibre in stalks, feathering and lateral branch growth. Temperatures > 32°C, if picking frequency is not increased.
Capsicum	Very sensitive	All stages affected by cool temperatures	Tolerant	Reduced pollination and yield, sunburn on fruit.
Parsley	Moderate tolerance	All stages affected by cool temperatures	Tolerant	Tolerant
Potatoes	Low tolerance	Emergence to 8 weeks	Tolerant	Poor tuber set, secondary growth and heat sprouting.
Pumpkins	Very sensitive	All stages affected by cool temperatures	Tolerant	Poor fruit set
Radish	Tolerant	Emergence	Tolerant	Poor root quality
Rockmelon	Very sensitive	All stages affected by cool temperatures	Tolerant	Sunburn
Shallot	Tolerant	Emergence to 10 weeks	Tolerant	Tolerant
Silverbeet	Moderate tolerance	Emergence to 8 weeks	Tolerant	Tolerant
Sweet potatoes	Sensitive	All stages affected by cool temperatures	Tolerant	Tolerant
Cucumber	Very sensitive	All stages affected by cool temperatures	Tolerant	Lack of pollination
Eggfruit	Very sensitive	All stages affected by cool temperatures	Tolerant	Sunburn on fruit

Crop	Frost sensitivity	Specific frost-sensitive stage	High temperature sensitivity	Effects of prolonged hot weather
Watermelon	Very sensitive	All stages affected by cool temperatures	Tolerant	Sunburn
Zucchini & button squash	Very sensitive	All stages affected by cool temperatures	Tolerant	Poor pollination
Sweet corn	Very sensitive	All stages affected by cool temperatures	Tolerant, affected >35^{o}C	Pollination problems, poor kernel development, poor husk cover, tasselate ear.

Source: Based on QDPI information http://www.daff.qld.gov.au/26_15331.htm with modifications.

3.2.4 Case study: Lettuce

Lettuce germination and early growth rate are largely determined by temperature. The apical meristem of young lettuce plants is near the soil surface, so soil temperature is often more closely correlated with early plant growth rate than is air temperature. Production of high-quality lettuce generally requires a cool, mild climate. The optimum average temperature for lettuce growth is 18°C. The most successful commercial lettuce production in Australia occurs during periods of the year when there are at least two months with maximum daytime temperatures of between 17 and 28°C with night-time temperatures that do not exceed 15°C.

Temperature sensitivity studies have shown that when the average temperature increased from 16.3 to 21.1°C, early-season growth rate increased but the crop duration was shortened, and this reduced yield by 17%. This is characteristic of determinate crops and other studies have reported a similar negative relationship between temperature and head weight and density of Iceberg lettuce[64].

Temperatures that exceed specific warm temperature thresholds can cause premature 'bolting' (elongation of internodes of the main stem to form a seed stalk) and lead to severe reductions in marketable yield in lettuce. Some research suggests that night temperature is more critical than day temperature with regard to flower induction and bolting. Flowering of Iceberg head lettuce occurs 21 days earlier with night temperatures of 21°C compared with 16°C. There is genotypic variation in the specific temperature for flower induction, and there has been some success at developing varieties resistant to bolting at night temperatures that exceed 15°C.

Tipburn, a physiological disorder of lettuce is often associated with rapid growth rates at warm temperature and high humidity. It is characterised by necrosis of the edges of young, rapidly expanding leaves. Just a few days of high temperature can have a sufficient negative effect on the visual quality of Iceberg and Cos lettuce to lead to a complete crop failure. The disorder has been well studied and is known to be associated with localised calcium deficiency, which results when leaf expansion is faster than the mobility of calcium in the plant. Improving soil calcium availability does not alleviate the problem. While foliar application of calcium to susceptible, rapidly expanding leaves is sometimes partially effective in loose-leaf types, it is not a practical solution.

Carbon dioxide enrichment, typically to levels of about 1000–1200 ppm has been used commercially to increase yields of greenhouse-grown lettuce. Quantitative scientific assessments of lettuce response to CO_2 indicate about a 50% increase in total dry weight when plants are grown at 1000–1200 compared with current ambient CO_2 levels.

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[64] D.C.E. Wurr et al, (1996) Investigating trends in vegetable crop response to increasing temperature associated with climate change . Scientia Horticulturae 66 255-263.

Yields were estimated for lettuce from a doubling of CO_2 levels and associated predicted climatic changes. Negative effects on yield from climatic change were compensated to some extent by the direct beneficial effects from a doubling of CO_2. The predicted maximum fresh-weight yields with climatic change are reduced by only about 5% compared with the current conditions. These results suggest that in those cases where temperatures do not reach thresholds that cause bolting, tipburn, or other problems that lead to a serious loss of marketable yield, the yield reductions in a future high-CO_2 world would be small, and in some situations the shorter crop duration may allow an additional planting in a single season. (Case study adapted from Peet and Wolfe [65].)

3.2.5 Case study: Carrot

Carrots, like most other vegetable root crops are adapted to cool temperatures. The optimum temperature for carrot root growth is in the range of 15–18°C, however differential effects on root and shoot temperature is more complicated. Increasing shoot temperature from 15 to 25°C while holding the root at 15°C is predicted to increase shoot weight by about 36% while decreasing root weight slightly.

Because carrot roots store photosynthate, it has been suggested that the yield of crops such as carrot may be very responsive to increasing the atmospheric CO_2 concentration. Yield increases from a doubling of CO_2 of as much as 110% have been reported for carrot, but these results should not be viewed as typical.

In a study involving tunnels where the temperature ranged from of 7.5 to 10.9°C, a 31% increase in root weight was observed at high CO_2 (550 ppm) compared to current levels and a small, but consistent, increase of about 5% in the root/total dry weight ratio. On average, root yields increased about 34% for each 1°C increase in temperature, and most of the increase in yield due to temperature was attributable to faster growth rate and development at warmer temperatures[66].

In contrast, another study reported a significant CO_2 by temperature interaction for carrot yields, with more than twofold yield increases at relatively warm temperatures and little benefit of higher CO_2 at temperatures below 12°C. More research at warmer temperatures approaching the stress level for carrot would be valuable in attempting to anticipate the effects of climatic change on this crop species. (Case study adapted from Peet and Wolfe[65].)

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[65] Peet, M. M. and D. W. Wolfe (2000). Crop ecosystem responses to climatic change: vegetable crops.
[66] Wurr, D. C. E. (1998) Climate change: a response surface study of the effects of CO2 and temperature on the growth of beetroot, carrots and onions. Journal of Agricultural Science, Cambridge 131, 125±133

3.2.6 Impacts of predicted changes on vegetable disease

Impacts on plant diseases in general. With climate change, changes will occur in the type, amount and relative economic importance of pathogens and diseases. This will alter the spectrum of diseases, particularly for pathogens with alternate and alternative hosts. As host species slowly migrate to new areas, new disease complexes may arise while some diseases will cease to be economically important. There may be an increase in severity of many diseases that are dependent on moisture for development and spread. Evolution of pathogen populations may accelerate from enhanced UV-B radiation and/or increased fecundity in elevated CO_2 and as a result, host resistances may be overcome more rapidly. Climate change may alter the suitability of a crop for certain locations; however, crops may continue to be grown for agro-ecological or economic reasons. Chronic stress from marginal climates would lead to progressive deterioration in plant health and increased susceptibility to diseases, and this will be more pronounced in perennials. Soil-borne pathogens can be expected to spread to new areas and once introduced, will be difficult to control due to a lack of effective measures. Disease management will be influenced due to altered efficacy of biological and chemical control options[67].

Vegetable diseases. The impact on diseases affecting the vegetable industry can be described by two contrasting case studies relating to target spot (caused by *Alternaria solani*) of potato and tomato and Verticillium wilt of tomato.

Development of target spot is very strongly influenced by the physiological status of the host. Host susceptibility increases as tissue ages or is stressed due to poor nutrition or root disease. Temperature, relative humidity and hours of leaf wetness modify sporulation, germination/infection and growth of the fungus. Considering the knowledge available, the impact of climate change on this disease would be to enhance resistance through the elevated CO_2 effect and to enhance sporulation and infection through increased summer rainfall. Under climate change, damage from target spot will depend on the balance between enhanced host plant resistance and increased pathogen sporulation and infection opportunities.

Verticillium wilt is sensitive to temperature. The pathogen has limited saprophytic ability and survives as microsclerotia in the absence of a host. Two forms with different tolerance to high temperature are recognised[68] and the microsclerotial strain could tolerate higher temperatures than the dark mycelial strain. In Australia, the microsclerotial strain is by far the most common.

Verticillium wilt is widely distributed in Queensland, in particular on tomatoes and potatoes in the southeast and on peanuts at Kingaroy. It is present on a few tomato farms in the

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[67] Chakraborty, S., G. M. Murray, et al. (1998). "Potential impact of climate change on plant diseases of economic significance to Australia." Australasian Plant Pathology 27(1): 15-35.

[68] Edgington, L. V. (1962). "Influence of Connecticut temperatures on the relative pathogenicity of Maine and Connecticut Verticillium isolates." American Potato Journal

Bundaberg district but is not severe and is not spreading. It does not affect tomatoes at Bowen but occurs in peanut and potato crops in the tropics on the elevated (700 m) Atherton Tableland. Verticillium wilt in tomato crops can be readily controlled by soil solarisation to raise the average daily maximum temperature at 7.5 cm depth by 10°C. The fungus can be eradicated from infected stem pieces in less than 24h at 45°C. Under climate change this sensitivity to temperature may make this disease less important in marginal areas such as Bundaberg and even the Lockyer Valley[69].

3.2.7 Impacts of predicted changes on vegetable pests

This review is adapted from an analysis of the impacts of climate change on pests by Gutierrez[70]. In the face of climate change, one could envision the invasion of new areas by pests formerly limited by one or more constraints. Boll weevil is limited by desiccation of fruit buds in hot dry areas; hence increased summer rainfall might extend its geographical range in formerly dry areas. This occurred during the early 1980s, when a sequence of very wet years in Arizona and southern California, coupled with the cultivation of stub-cotton, temporarily increased the threat from boll weevil.

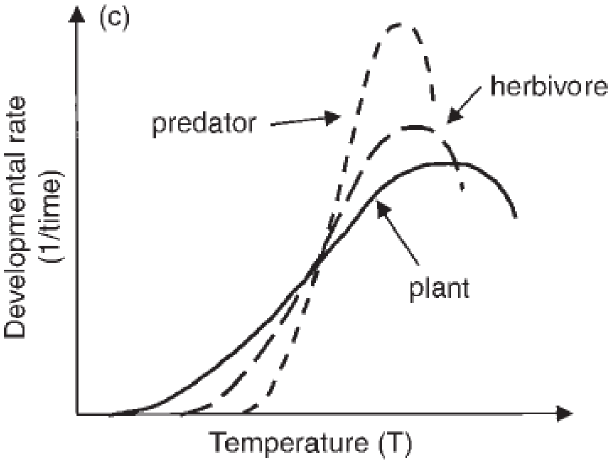

Figure 28. The hypothetical developmental rates on temperature of a plant, a herbivore and a predator[71]

Early studies by Fitzpatrick and Nix[72] and Gutierrez et al.[73] predate the advent of modern GIS, which can now quickly capture and map regional data. The climate-matching GIS-based

[69] Chakraborty, S., G. M. Murray, et al. (1998). "Potential impact of climate change on plant diseases of economic significance to Australia." Australasian Plant Pathology 27(1): 15-35.
[70] Gutierrez, A. P. (2000) Crop Ecosystem Responses to Climatic Change: Pests and Population Dynamics. In Climate change and global crop productivity. CABI Publishing.
[71] Gutierrez, A. P. (2000) Crop Ecosystem Responses to Climatic Change: Pests and Population Dynamics. Climate change and global crop productivity. R. K.R. and H. H.F., CABI Publishing.
[72] Fitzpatrick, E.A. and Nix, H.A. (1970) The climatic factor in Australian grasslands ecology. In: Moore, R.M. (ed.) Australian Grasslands. Australian National University Press, Brisbane, pp 3–26.

model CLIMEX is also based on the Fitzpatrick–Nix approach; it uses 30-year weather averages and includes areas outside of Australia. This algorithm has been used effectively to map the potential range of the Russian grain aphid *Diuraphis noxia*, the pathogen *Phytophthora cinnamoni* on *Quercus* spp. and other pests. Its successful application has occurred because the Fitzpatrick–Nix indices capture the shape of some essential biology.

Some species may quickly reach outbreak proportions when conditions become favourable. In North Africa and the Middle East, desert locust numbers decline during periods of drought, but quickly explode from barely detectable numbers during prolonged region-wide rainy periods, similar to that of the cowpea aphid in Australia. Under current weather, it might not be necessary to know the population dynamics of such species per se, but only whether conditions favour their increase and for how long. The growth index approach worked well for the highly migratory cowpea aphid but would it work equally well for locust in the vast affected areas of North Africa and the Middle East, an area many times larger than southeast Australia? The current limitation to this approach is the lack of infrastructure for collecting the requisite weather data, and the unreliability of rainfall predictions using satellite remote sensing over this large landmass. If this data gap could be overcome, physiologically-based models could provide a good way to evaluate the effects of weather and climate change on pest dynamics regionally using real-time weather.

What would happen to species such as desert locust in North Africa or cowpea aphid that are not regulated by natural enemies if the rainfall increased in response to climate change? Would cowpea aphid and desert locust population outbreaks be more frequent and prolonged? These are difficult questions to answer and require simplified but realistic models. The models proposed by Gutierrez[74] , Schreiber and Gutierrez[75] may be useful in answering such issues. However, field data and intuition suggest that the exotic cowpea aphid would become a more serious problem requiring new biological control agents, and possibly fungal pathogens might become more important than desert locust. In any case, the analysis would require a tritrophic perspective, and if feasible the results could easily be embedded in a GIS system. In areas with greater infrastructure, linking of biologically rich models for pest/crop (e.g. cotton) systems in GIS would provide important information on their interactions as modified by weather, including the effects of climate change.

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[73] Gutierrez, A.P., Havenstein, D.E., Nix, H.A. and Moore, P.A. (1974) The ecology of Aphis craccivora Koch and subterranean clover stunt virus. III. A regional perspective of the phenology and migration of the cowpea aphid. Journal of Applied Ecology 11, 21–35.
[74] Gutierrez, A.P. (1996) Applied Population Ecology: a Supply–Demand Approach. John Wiley & Sons, New York, 300 pp.
[75] Schreiber, S. and Gutierrez, A.P. (1998) A supply–demand perspective of species invasions and coexistence: applications to biological control. Ecological Modelling 106, 27–45.

3.2.8 Impacts of predicted changes on weeds

In a review of the potential impact of climate change on the interaction between crops and weeds, Bunce and Ziska[76] conclude the following: The ongoing increase in the concentration of carbon dioxide in the atmosphere, as well as potential changes in temperature and precipitation, may have important consequences for crop losses due to weeds. The physiological plasticity of weeds and their greater intraspecific genetic variation compared with most crops could provide weeds with a competitive advantage in a changing environment. However, because so little experimental work on crop/weed interactions under global change conditions has been carried out under field conditions, it is premature to conclude the magnitude or direction of changes in the interactions.

Despite the lack of direct experimental evidence, several effects are likely. One is that C_3 species (which includes most vegetable crops) will be favoured relative to C_4 species (such as sweet corn) as CO_2 increases, although there will be exceptions. The fact that many weeds are C_4 and most crops are C_3 may seem an advantage but will be of little comfort to those trying to grow C_4 crops in competition with C_3 weeds.

A second likely outcome, driven by increased CO_2 itself and potentially exacerbated by warming, is that some tropical and subtropical weeds will extend their ranges toward lower latitudes and become troublesome in areas where they are not currently a problem. Thirdly, and most speculative, because of the stimulation of seedling emergence and root and rhizome growth by increased CO_2, and because of decreased transpiration with increasing CO_2, weeds will be able to grow in drier soils and so weed control could become more difficult both for mechanical and chemical control measures.

Although much has been learned about responses to global change factors from studies of crops and weeds in controlled environment chambers and glasshouses, field facilities to simulate future environments are now sufficiently available that we urge the development of long-term field studies of crop/weed interactions and weed control under global change conditions.

Designing meaningful experiments will be challenging. Crop/weed interactions are local events, and generalisations about how interactions may change with global climate are best built from specific examples. Information obtained from such studies could be of substantial benefit in the development of new weed control strategies in a changing climate. There has not been a great deal of research into specific weed and crop interactions in response to climate change, however one study which evaluated the potential of four major weed species found evidence of evolutionary change in weed traits affecting invasiveness[77].

[76] Bunce, J. A. and L. H. Ziska (2000). Crop Ecosystem Responses to Climatic Change: Crop/Weed Interactions. Climate change and global crop productivity. R. K.R. and H. H.F., CABI Publishing

[77] Clements, D. R. and A. Di Tommaso (2012). "Predicting weed invasion in Canada under climate change: Evaluating evolutionary potential." Canadian Journal of Plant Science 92(6): 1013-1020

3.2.9 Summary of the expected impacts of climate change on vegetable production

Increasing CO_2 will enhance photosynthesis and improve water-use efficiency, thus increasing yield in most crops. Relative benefits from increased CO_2 often can be maintained with modest water and N deficiency, but yield benefits on an absolute basis are reduced when water or N limit growth.

The impact of increasing temperatures is more difficult to predict. Seed germination will probably be improved for most vegetables, as will vegetative growth in regions where mean daily temperatures during the growing season remain under 25°C, assuming adequate water is available.

Reproductive growth (flowering, fruit set and fruit development) is extremely vulnerable to periods of heat stress in many important vegetable fruiting crops, such as tomato, capsicums, bean and sweet-corn, and yield reductions will probably occur unless production is shifted to cooler portions of the year or to cooler production regions. This vulnerability results from the shortened duration of grain, storage tissue, or fruit-filling and from failure of various reproductive events, especially the production and release of viable pollen.

Processing crops, which are sometimes direct-seeded and are more frequently grown in cool-summer areas, are more likely than fresh-market crops to benefit from higher temperatures. In general, crops with a high harvest index, high sink demand, indeterminate growth and long growth seasons are considered most likely to respond positively to the combination of higher CO_2 and temperature.

Leafy vegetables and most brassica crops are, in the main, cool-season crops, so heat stress during the growing season would be detrimental to these species. High-temperature effects on lettuce and spinach and low-temperature effects on brassica crops include induction of flowering and elongation of the seedstalk. Planting dates, production areas and cultivars may need to be adjusted if temperatures change as predicted. (Adapted from Peet and Wolfe[78].)

[78] Peet, M. M. and D. W. Wolfe (2000). Crop ecosystem responses to climatic change: vegetable crops.

4 Climate change credentials of the Australian vegetable industry – How are we doing?

Agriculture in Australia last year (2012) emitted 88.4 Mt CO2-e, which was about 16% of the total emissions for Australia, and was 1.6% higher than 1990 emissions (Table 6). The emissions from agriculture are mainly carbon dioxide, methane and nitrous oxide, and the agriculture sector is the dominant source for both methane from ruminant animals and nitrous oxide, mainly from nitrogen fertilisers.

Table 6. National greenhouse gas emissions by sector 2011/2012 [79]

Sector	Annual emissions (Mt CO_2-e) Year to September 2011	Year to September 2012	Change (%)
Energy – Electricity	196.1	190.7	-2.8%
Energy – Stationary energy excluding electricity	93.7	92.4	-1.3%
Energy – Transport	85.6	87.6	2.3%
Energy – Fugitive emissions	41.6	41.9	0.8%
Industrial processes	32.7	31.1	-5.0%
Agriculture	85.4	88.4	3.5%
Waste	14.1	14.1	0.3%
National Inventory Total (excluding LULUCF)	**549.1**	**546.1**	**-0.5%**

The Australian horticulture industry only emits about 0.7MT of CO_2-e per year, which is about 1% of the total emissions for agriculture. These emissions rose steadily from 1990 but have been relatively constant since 2001 (Figure 29).

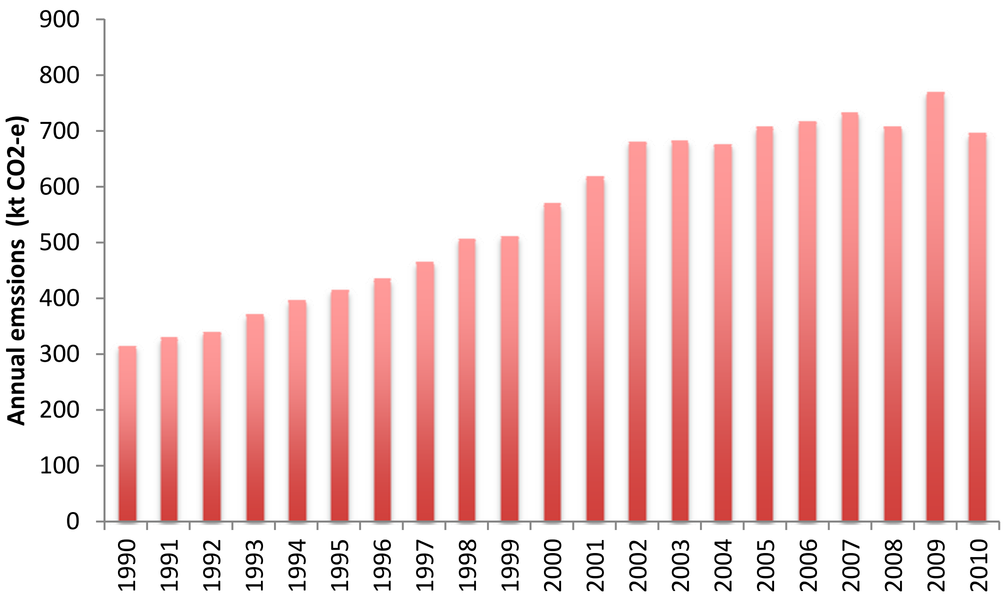

Figure 29. Annual greenhouse gas emissions from the Australian horticulture industry (2010): Source AGEIS.

[79] DCCEE (2013). Quarterly Update of Australia's National Greenhouse Gas Inventory: September Quarter 2012. Australian National Greenhouse Accounts. Canberra.

There is a lack of data available for the accurate calculation of direct greenhouse gas emissions from Australian vegetable farms. The main problem is that few studies have been conducted to date that have measured soil emissions, especially nitrous oxide, and also the long-term impacts on soil carbon. The only studies available to date are:

- A DAFF-funded demonstration project on greenhouse gas emissions in vegetable crops at sites in Queensland and Victoria[80] .
- A HAL project in NSW that collected baseline emissions data for lettuce, broccoli, cabbage, and potatoes and measured the impact of no-till and organic supplements on greenhouse gas emissions[81].

There are more studies in progress; refer to the Australian research component of this review for details (Section 8.1). A large research project with a focus on nitrous oxide and vegetables was funded in round 2 of the Filling the Research Gap program[82].

The vegetable industry and HAL sponsored a project in 2008 aimed at carbon footprinting for the Australian vegetable industry[83]. As part of this project there were six discussion papers produced, including discussion paper 4 which produced a preliminary estimate of the carbon footprint for the Australian vegetable industry[84]. The same data was also published separately as a paper entitled *An assessment of greenhouse gas emissions from the Australian vegetables industry*[85]. This work also led to the development of a carbon footprinting tool developed for the vegetable industry[86].

80 Melville, P., I. Poorter, et al. (2013). Carbon and sustainability – A demonstration of how they relate and how they can be managed within the Australian Vegetable Industry.
81 Rogers, G. and M. K. D. Hall (2012). Quantifying the effects of no-till vegetable farming and organic mulch on emissions and soil carbon. Applied Horticultural Research.
82 Department of Agriculture, Fisheries and Forestry: DAFF www.daff.gov.au
83 VG08107: Vegetable Industry Carbon Footprint Scoping Study – Discussion Papers and Workshop
84 Rab, M. A., P. D. Fisher, et al. (2008). Vegetable Industry Carbon Footprint Scoping Study – Discussion Papers & Workshop. 4. Preliminary Estimation of the Carbon Footprint of the Australian Vegetable Industry.
85 Maraseni, T. N., G. Cockfield, et al. (2010). "An assessment of greenhouse gas emissions from the Australian vegetables industry." Journal of Environmental Science and Health. Part B, Pesticides, Food Contaminants, and Agricultural Wastes 45(6): 578-588.
86 http://www.vegiecarbontool.com.au/

4.1 How does horticulture and vegetables compare to other industries?

The Australian vegetable industry is a relatively small emitter of greenhouse gases due to its small total area of cultivation (about 110,000 ha), the greenhouse gas emission from the vegetable sector have been estimated at between 1.0[87] and 1.1[88] MT CO_2-e/year from direct and indirect emissions. The total emissions for horticulture are only 1% of agriculture or 0.12% of the national total. Vegetables are even less, at 0.05% of total emissions (Table 7).

The horticultural and vegetable sectors have a very low rate of emissions per $ of value produced. The vegetable sector produces 85 t CO_2-e for every $1M in revenue generated and the horticulture industry generally produces 83 t CO_2-e for every $1M in revenue generated (at the farm gate). These are excellent figures relative to other rural industries and small compared to the big polluters such as power generation and aluminium.

Table 7 Emissions intensity of industries[89]

Ranking	Industry sector	Emissions / Revenue (t CO2-e/$M revenue)	% National emissions
1	Electricity supply	9,945	5.0
2	Aluminium	7,357	6.1
3	Beef cattle	6,687	11.2
4	Cement and lime	4,720	1.4
5	Sheep	3,513	3.4
6	Dairy cattle	3,240	2.7
7	Pigs	1,958	0.4
9	Vegetables	85	0.05
8	Horticulture	83	0.12

On a per-hectare basis however, this puts CO_2-e emissions intensity of vegetables at between 8.7[90] and 9.3[91] T CO_2-e/ha/year. Direct soil emissions from vegetables are about 0.2 MT CO_2-e/year or about 1.8 T CO_2-e/ha/year – virtually all as nitrous oxide[92]. These emission rates are high compared to wheat where emission rates range from 198 to 348 kg CO_2-e /ha/year[93].

87 Rab, M. A., P. D. Fisher, et al. (2008). Vegetable Industry Carbon Footprint Scoping Study – Discussion Papers & Workshop. 4. Preliminary Estimation of the Carbon Footprint of the Australian Vegetable Industry.
88 Maraseni, T.K. et al., (2010) An assessment of greenhouse gas emissions from the Australian vegetables industry. Journal of Environmental Science and Health Part B 45, 578–588.
89 Source: DCCEE CPRS 2010 with modifications
90 Rab, M. A., P. D. Fisher, et al. (2008). Vegetable Industry Carbon Footprint Scoping Study – Discussion Papers & Workshop. 4. Preliminary Estimation of the Carbon Footprint of the Australian Vegetable Industry.
91 Maraseni, T.K. et al., (2010) An assessment of greenhouse gas emissions from the Australian vegetables industry. Journal of Environmental Science and Health Part B 45, 578–588.
92 http://www.carbonneutral.com.au/climate-change/australian-emissions.html
93 Scheer, Clemens, Grace, Peter R., Rowlings, David W., & Payero, Jose (2012) Nitrous oxide emissions from irrigated wheat in Australia : impact of irrigation management. Plant and Soil, 359(1-2), pp. 351-362.

The area where vegetable production emissions are high is in the use of electricity for pumping and cooling. These emissions are counted in the electricity generation pool and not allocated to agriculture directly. The following section on carbon footprinting does include these indirect emissions.

4.2 The Australian vegetable industries carbon footprint

The carbon footprinting protocol classifies emissions into three categories or scopes depending on whether the emissions are emitted directly as part of the activity (Scope 1) or of they are emitted indirectly by using inputs that emit greenhouses gases in their manufacture or distribution (Scope 3). Electricity purchased for the operation has its own category (Scope 2) (Table 8).

Table 8 Types of carbon emissions. Source KPMG[94].

	Scope 1	Scope 2	Scope 3
Emission type	Direct	Indirect	Embodied
	Emissions from within the organisation	Emissions from purchased electricity	Emissions embedded in inputs
Examples	• Electricity generation • Industrial processes • Fuel usage for transporting inputs • Fugitive emissions • On site waste	• Electricity consumption	• Waste disposal • Purchased materials • Business travel • Fuel usage for transporting outputs • Outsourced activities
Supply chain	Impacted	Impacted	Impacted
Mandatory reporting (NGERS)	Report (if > threshold)	Report (if > threshold)	Voluntary
Emissions trading (CPRS)	Liable (if > threshold and at point of obligation)	Impacts compensation calculations only	

HAL project VG08107, “Vegetable Industry Carbon Footprinting Scoping Study” produced an estimate of total greenhouse gas emissions from the vegetable industry and these are outlined in Table 9. The distribution of the various sources is shown in Figure 30. The major sources of greenhouse gas emission for the Australian vegetable industry in order of magnitude are:

1. Electricity for pumping irrigation water.
2. Direct farm emissions, mainly nitrous oxide emissions from nitrogen fertiliser.
3. Electricity for running cool-rooms.

[94] KPMG (2009). Managing financial impacts and reporting of carbon emissions : A guide for CFOs.

Table 9. Annual greenhouse emissions for the Australian vegetable industry. Source[95]

Source of emissions	Type / Scope	T CO_2-e / year
Fertiliser	Indirect 3	81,362
Agrochemicals	Indirect 3	6,375
Electricity for irrigation	Indirect 2	534,860
Electricity for cool-rooms	Indirect 2	155,000
Fuel production	Indirect 3	10,834
	Total indirect	**788,431**
Soil emissions	Direct 1	195,556
Diesel use on farm	Direct 1	63,021
	Total direct	**258,577**
	Total	**1,047,008**

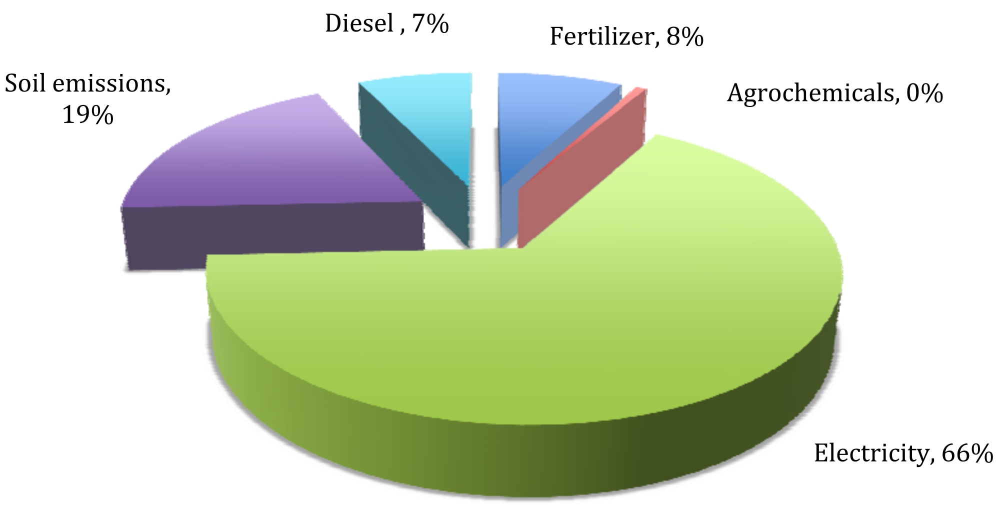

Figure 30. Distribution of greenhouse emissions for the Australian vegetable industry[96]**.**

[95] Rab, M. A., P. D. Fisher, et al. (2008). Vegetable Industry Carbon Footprint Scoping Study – Discussion Papers & Workshop. 4. Preliminary Estimation of the Carbon Footprint of the Australian Vegetable Industry.
[96] Rab, M. A., P. D. Fisher, et al. (2008). Vegetable Industry Carbon Footprint Scoping Study – Discussion Papers & Workshop. 4. Preliminary Estimation of the Carbon Footprint of the Australian Vegetable Industry.

4.3 Carbon emissions by crop

4.3.1 Total emissions for each vegetable industry

Considering greenhouse gas emissions on an industry-wide basis, the total emissions including those produced on farm and those associated with producing inputs required to produce the crop, the results are shown in Figure 31. The differences in total emissions by industry are due mainly to the areas of crop produced, and so the major crops such as potatoes and lettuce figure highly in total emissions numbers.

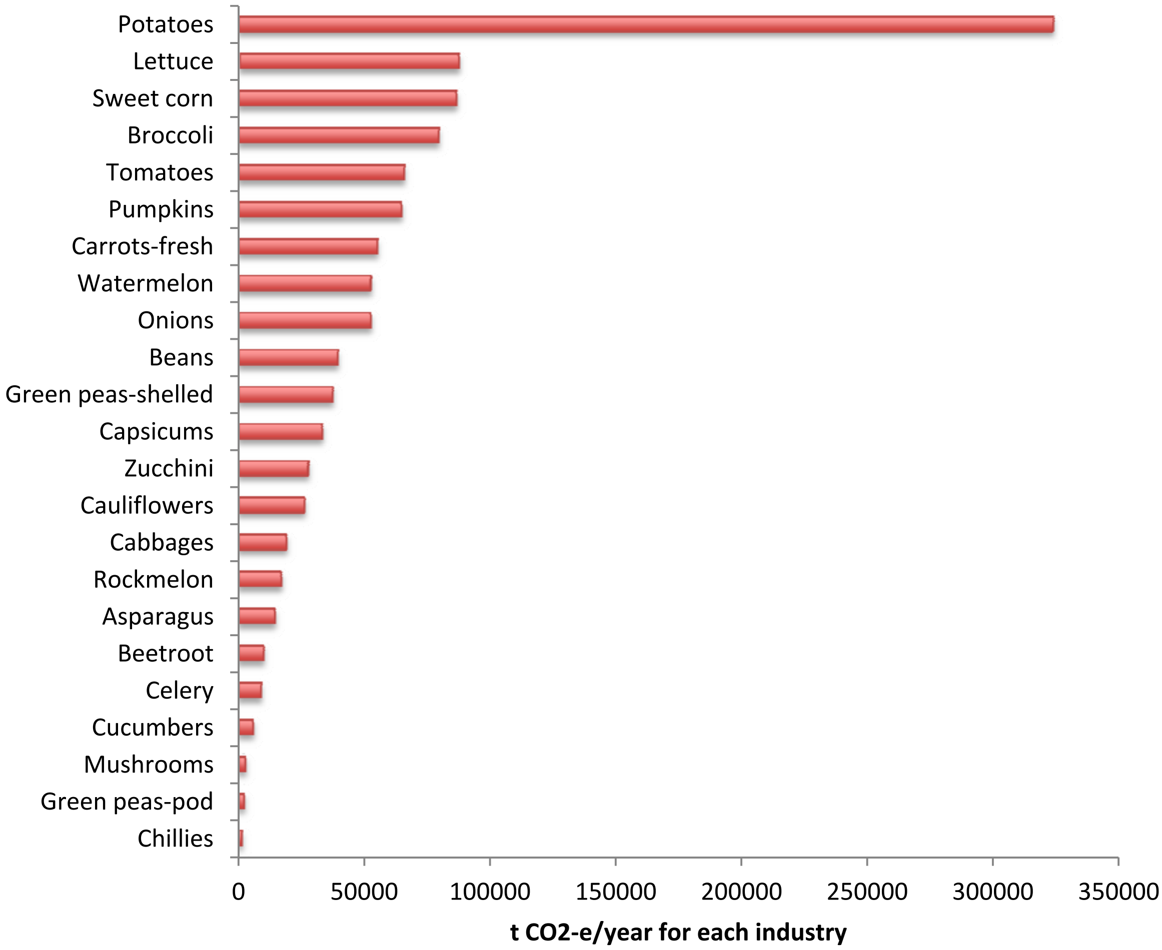

Figure 31 Total CO_2-e emissions for each vegetable industry[97]

[97] Maraseni, T.K. et al., (2010) An assessment of greenhouse gas emissions from the Australian vegetables industry. Journal of Environmental Science and Health Part B 45, 578–588.

4.3.2 Vegetable crop emissions intensity on an area basis

When the emissions intensity per hectare of crop is considered, vegetable crops are ranked as shown in Figure 32. The highest is capsicum with an intensity of 15.4 tonnes CO_2-e per ha and the lowest is rockmelon at 6.4. The average greenhouse gas intensity for vegetables is 9.2 t CO2-e/ha, which is high relative to other broad acre crops such as wheat.

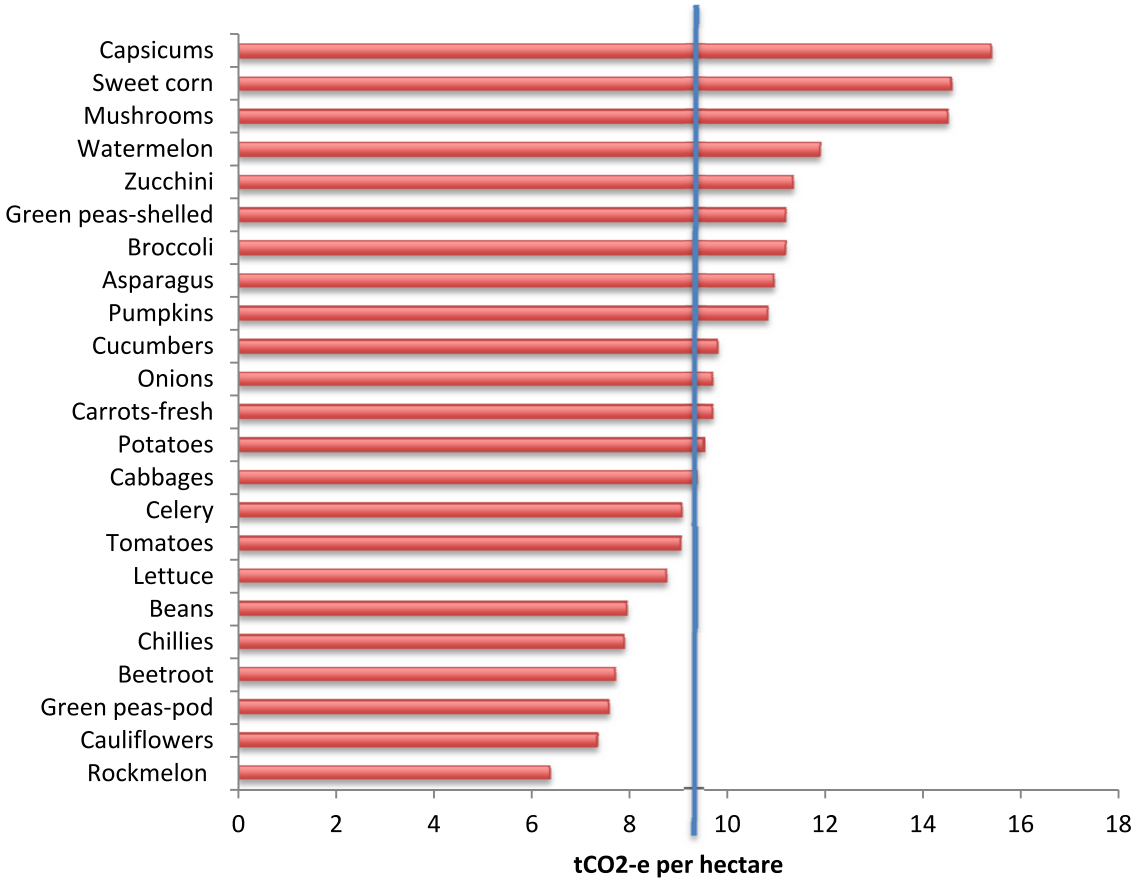

Figure 32 CO_2-e emissions intensity per crop on an area (hectare) basis. The blue line shows the industry average emissions intensity of 9.2 t CO2-e/ha [98]

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[98] Maraseni, T.K. et al., (2010) An assessment of greenhouse gas emissions from the Australian vegetables industry. Journal of Environmental Science and Health Part B 45, 578–588.

4.3.3 Vegetable crop emissions intensity on per tonne of crop produced basis

When greenhouse gas emissions intensity is considered on a per tonne of produce basis, it is the low-yielding crops that have the highest intensity. The highest crops are green peas and asparagus, and the lowest are carrots celery and cucumbers (Figure 33).

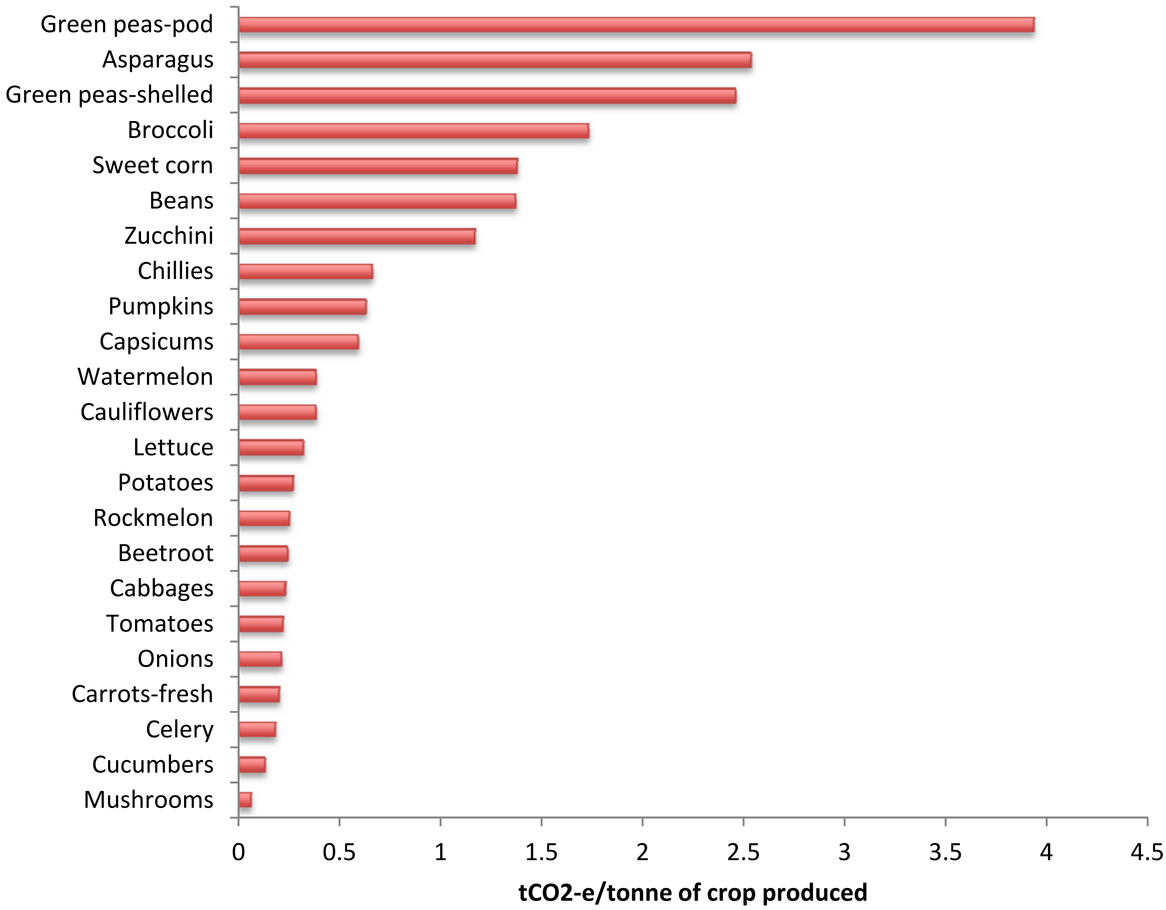

Figure 33 CO_2-e emissions intensity per tonne of crop basis[99]

[99] Maraseni, T.K. et al., (2010) An assessment of greenhouse gas emissions from the Australian vegetables industry. Journal of Environmental Science and Health Part B 45, 578–588.

Table 10 is a summary of all the data presented in the figures above and also shows the total GHG emissions for vegetables of 1.1 Mt CO_2-e per year as calculated by Maraseni et al. (2010).[100]

Table 10 Summary table of CO_2-e emissions for vegetables in Australia[100]

	CO_2-e Emissions (tonnes)		
Crop	**Per Year**	**Per hectare**	**Per tonne crop**
Asparagus	14251	10.95	2.54
Beans	39547	7.94	1.37
Beetroot	9845	7.70	0.24
Broccoli	79820	11.19	1.73
Cabbages	18945	9.38	0.23
Capsicums	33202	15.40	0.59
Carrots-fresh	55357	9.69	0.20
Cauliflowers	26276	7.34	0.38
Celery	8975	9.06	0.18
Chillies	1285	7.88	0.66
Cucumbers	5657	9.80	0.13
Green peas-pod	2098	7.57	3.94
Green peas-shelled	37531	11.19	2.46
Lettuces	87642	8.75	0.32
Rockmelon	16720	6.36	0.25
Watermelon	52619	11.90	0.38
Mushrooms	2626	14.51	0.06
Onions	52452	9.69	0.21
Potatoes	324145	9.51	0.27
Pumpkins	64635	10.83	0.63
Sweet corn	86628	14.58	1.38
Tomatoes	65999	9.05	0.22
Zucchini	27643	11.34	1.17
Total	**1,113,897**		

[100] Maraseni, T.K. et al., (2010) An assessment of greenhouse gas emissions from the Australian vegetables industry. Journal of Environmental Science and Health Part B 45, 578–588.

5 Changing supply-chain and consumer expectations

In recent years the supply-chain and consumers have become more aware of the environmental impact of food production. This has seen a range of issues aggregate under the sustainability umbrella such as: food miles; local produce (farmers markets); water and carbon footprinting; and organic.

International standards have been developed to understand how food impacts on the environment. Life Cycle Assessment (LCA) is a key tool for analysing the cumulative environmental impacts through the entire life cycle of a product. This "cradle-to-grave" approach considers resource extraction (e.g. energy, water) and emissions (to air, water and soil) during the production, transport, consumption and disposal of a product. International standards ISO 14040 and ISO 14044 apply to the development of LCAs[101,102].

In 2010, Italian food company Barilla created the double pyramid[103]. The double pyramid combines the familiar food pyramid with a newly developed environmental pyramid.

Together these two pyramids summarise healthy food for people and also sustainable food for the planet (Figure 34). The double pyramid clearly illustrates the connection between two different but highly-relevant goals: human health and environmental protection. By following the diet suggested in the traditional food pyramid, not only do people live longer and healthier lives, but there can be less environmental impact.

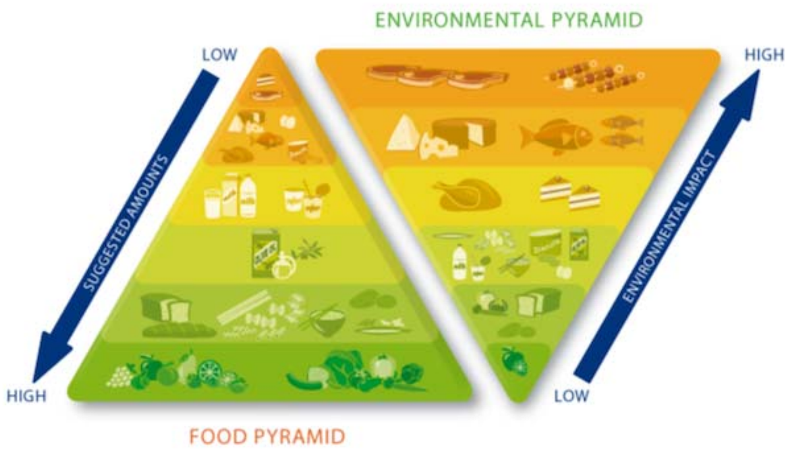

Figure 34. The Barilla Centre for Food Nutrition's double pyramid was developed to communicate the connection between two different but highly-relevant goals: health and environmental protection.

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101 ISO 2006a, ISO 14040:2006 Environmental management – Life cycle assessment - Principles and framework, International Organization for Standardization, Geneva.
102 ISO 2006b, ISO 14044:2006 Environmental management – Life cycle assessment – Requirements and guidelines, International Organization for Standardization, Geneva.

103 Buchner, B Fischler, C Fitoussi, J Monti, M Riccardi, G Ricordi, C Sassoon, J Veronesi, U 2010. Double Pyramid: Healthy food for people, sustainable for the planet. Barilla Center for Food & Nutrition, Italy.

Underlying the Barilla environmental pyramid is detailed assessment of the impact of food on the environment, drawn from 334 reports[104]. Three indicators are used – carbon, water and ecological footprints – with the results for carbon shown in Figure 35.

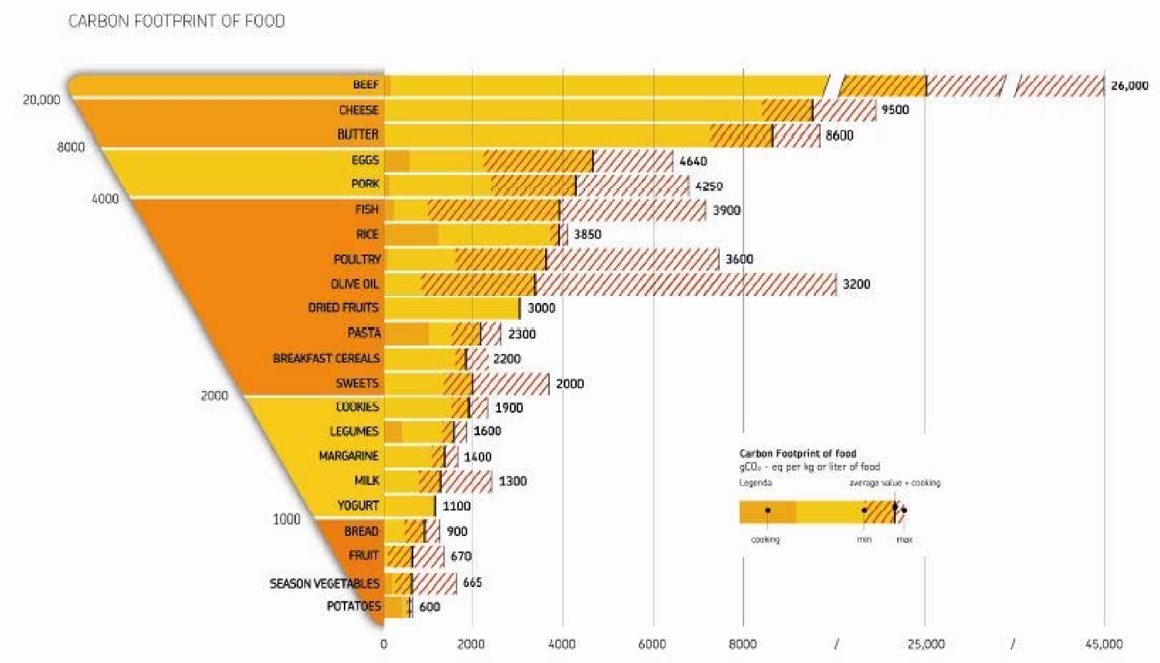

Figure 35. Carbon footprint of food production, produced by Barilla Centre for Food Nutrition[105].

Vegetables are at the bottom of the carbon footprint pyramid, which is a positive for the industry, and an opportunity to promote the good climate change credentials of the vegetable industry.

The supply chains want environmental assurance to be kept simple and low cost, to be built into their existing industry standards and to add value to their businesses. As a starting point, several agricultural industry organisations favour the use of a basic management system, combining continuous improvement, risk assessment and industry best management practice programs, which can be built on over time to meet regulator, market and community expectations.

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104 Bassi, R. Bastianoni, S. Bianchi, M. Briante, E. Campra, L. Ciati, R. De Biasio, A. Esposito, E. Faraon, S. Filareto, A. Lemma, V. Maffeis, C. Marchelli, L. Marino, M. Meriggi, P. Morsellino, M. Neri, E. Niccolucci, V. Pignatelli, S. Pizzi, C. Alberto, C. Ruini, L. Ruggerini, A. Sessa, F. 2011. 2011 Double Pyramid: Healthy food for people, sustainable for the planet. Supporting technical paper. Version 2 of 14 July 2011. Barilla Center for Food & Nutrition, Italy.

105 Bassi, R. Bastianoni, S. Bianchi, M. Briante, E. Campra, L. Ciati, R. De Biasio, A. Esposito, E. Faraon, S. Filareto, A. Lemma, V. Maffeis, C. Marchelli, L. Marino, M. Meriggi, P. Morsellino, M. Neri, E. Niccolucci, V. Pignatelli, S. Pizzi, C. Alberto, C. Ruini, L. Ruggerini, A. Sessa, F. 2011. 2011 Double Pyramid: Healthy food for people, sustainable for the planet. Supporting technical paper. Version 2 of 14 July 2011. Barilla Center for Food & Nutrition, Italy.

5.1 Comments from the major retailers in Australia

5.1.1 Woolworths

Opinion from Woolworths on the importance of the greenhouse gas emissions is that they are not an important factor in consumers buying decisions. At present there is no suggestion that measures such as carbon or water footprints, or food miles would be used in the marketing of vegetables in Australia[106].

Woolworths however are committed to a 40% reduction in carbon emissions on project growth levels by 2015, maintaining 2006 levels; a 25% minimum reduction in carbon emissions per square meter for all new stores compared to existing stores; and a 25% reduction in carbon emissions per carton delivered by Woolworths-owned trucks by 2012[107].

5.1.2 Coles

Australian consumers prefer Australian grown because they consider the produce clean, green and safe. They assume that environmental issues are well managed. Customers care about these things.

The Australian vegetable industry has good environmental credentials. Water is well managed. Carbon is not considered a high priority, however there could be some improvements in areas such as:

- Fertiliser usage including fertigation.
- Soil water management, especially avoiding waterlogging that leads to nitrous oxide emissions.
- Controlled traffic.
- Improved energy use efficiencies.

In terms of energy efficiencies, overseas there is more interest in solar panels (PV) and more energy efficient pumps.

There is some opportunity to manipulate cooling rates e.g. the apple industry is working with CSIRO to optimise the temperature management of apples. In general, Coles is confident the temperature requirements in vegetable crop specifications are correct; it is important to manage temperatures to avoid food waste and associated environmental impacts.

[106] Paul Harker, pers comm.
[107] http://woolworths.com.au/wps/wcm/connect/Website/Woolworths/About+Us/Our+Planet/

Improvement of electrical systems such as load management could reduce costs to grower/ packers, but in Australia the structure of rural energy tariffs do not always allow for these improvements.

Food miles are not a true reflection of carbon emissions with far greater emissions from customers taking produce home from the store than in transport from farms to DCs and to stores. [108].

[108] Andreas Kleiber pers comm.

6 Economic Impacts

The main components of this section are:

1. An Assessment of farm-level impacts of the carbon price on the gross margins of selected vegetable crops including beans, beetroot, broccoli, capsicums, carrots, cauliflower, sweet corn and lettuce.
2. An assessment the financial impact of changes in vegetable yields due to changes in temperature and rainfall associated with climate change, changes in the price of irrigation water associated with a range of drought conditions and implementation of electricity-use efficiency initiatives.

The assessment is based on the following data and information:

1. Gross margins for each of the selected vegetables from the Queensland Department of Agriculture, Fisheries and Forestry (DAFF) and gross margins for selected vegetable crops form the New South Wales Department of Primary Industries.
2. Data on water use, pumping and cooling costs (electricity costs) and crop yields under a range of conditions for the eight vegetable crops.
3. Irrigation water prices under normal and various drought conditions.
4. Farm-gate prices for vegetables.
5. Energy-efficiency improvement factor for electricity consumption in water pumping and cooling where relevant (25%).

These data and information were used in combination to formulate a set of scenarios for the financial analyses.

6.1 The method

Six scenarios were defined to reflect the following conditions:

1. **Baseline scenario** – This situation represents growing conditions prior to the introduction of the carbon price. The price of irrigation water set at $100/ML and average crop yields and normal growing conditions are assumed.
2. **Carbon price scenario** – This scenario modifies the baseline conditions with incorporation of the impact of the carbon price on the price of electricity used for pumping irrigation water and cooling harvested vegetables, where relevant. It is assumed that the retail price of electricity in Queensland increased by 10.4% (2.15c/kwh) based on the legislated $23 per tonne carbon price introduced by the Australian Government in July 2012.

3. **Carbon price and electricity use efficiencies** – Using the carbon price scenario, separate estimates are made of the percentage reductions in electricity use for pumping and cooling required to achieve the baseline gross margin. A similar calculation is made for water-use efficiency to estimate the percentage reduction in irrigation water required to achieve the baseline gross margin (i.e. the pre carbon price gross margin).
4. **Carbon price and climate-change induced higher temperatures** – This scenario modifies the carbon price scenario by reducing crop yields and increasing the price of irrigation water by 50% to $150/ML, reflecting moderate drought conditions. This scenario incorporates a demand response to the price of water resulting in a slight reduction in the water use. The scenario does not accommodate any efficiency gains associated with electricity use.
5. **Carbon price and severe drought** – This scenario captures the impact of a severe drought with the same yield reductions as for scenario 4, but with a significantly higher water price of $500/ML, reflecting the scarcity of irrigation water.
6. **Worst-case** – This scenario is the same as scenario 5 but with the price of water set at $1500/ML, to reflect the worst possible case for water availability.

The method of analysis involves modifying specific variables in the gross margins spreadsheet for each of the selected vegetables in accordance with the particular scenario being assessed. In the case of yields and water prices the modifications are straightforward. The basis of the variation to the price of electricity and the cost of pumping and cooling are explained in the next section. The basis of the water-use response to changes in the price of irrigation water is also explained.

6.2 The carbon price impact on electricity prices

The baseline retail price for electricity used in the gross margin analyses was $0.2067/kwh. A study by the Energy Economics and Management Group of the University Queensland in 2012 assessed the impact of the carbon price on electricity prices in the eastern states of Australia.[109] The study estimated an average increase in retail electricity prices of 8.9%. The estimated increase for Queensland was 10.4%, the biggest of the five eastern States. This reflects the State's relatively heavy reliance on coal-fired electricity generation. For the carbon price scenarios the price of electricity was increased by 10.4%. For example, the cost of water pumping was assumed to be $90/ML for most vegetables in the baseline scenario. The impact of the carbon price increased the cost of water pumping to $99.36/ML. Similar adjustments were made for the costs of cooling, which vary among the selected vegetables.

[109] Reported in *UQ News Online*: http://www.uq.edu.au/news/index.html?article=24612, accessed 20-03-2013

6.3 Demand response to changes in irrigation water prices

Approximately 90% of the land used for vegetable production in Australia is irrigated. The supply of irrigation water varies depending on dam replenishment rates and rates of consumption. Water pricing is used to ration water use. However, the responsiveness of water demand to changes in the price of irrigation water reflects the scope for adaptation in production by different users. In the case of vegetable production demand for water is relatively price inelastic. Bell et al (2007) found that the short-run price elasticity of demand for irrigation water in the vegetable industry was -0.83[110]. This means that for a 1% change in the price of irrigation water, vegetable growers would reduce water use by 0.83%. While this indicates that water use in vegetable production would not fall by much in the short term in response to higher prices and increasing water scarcity, it may be associated with water-use efficiency and operating close to technological limits[110]. Over the long term, changes can be made to irrigation infrastructure, other farm capital, land area and permanent labour supply, which may lead to more significant reductions in water use. The price elasticity of demand for water is factored into the high temperature, severe drought and worst-case scenarios, reflecting various conditions of water availability and water prices.

6.4 Limitations of the method

A gross margin is the difference between the total income generated by an enterprise in a given time period such as cropping season or year, and the variable costs incurred in the production of the crop in the same period. Variable costs vary with the area of crop and include seed, fertilizer, causal labour, pumping costs, fuel and oil, contractors, harvesting, packing and transport. A gross margin is not an absolute measure of profit as there is no account of capital (land, buildings, machinery, irrigation equipment, post harvest facilities etc) or fixed costs (depreciation, taxes, interest, rent, insurance and administration overheads including permanent farm labour). However, comparing gross margins for different crops or variations to costs, yields or input levels for the same crops provides a guide to the best options for a given set of fixed assets and a given time period.

While gross margins analysis allows comparison of different scenarios reflected in different values for cost, price, input and yield variables, it is a static analytical framework. The analysis can only produce short-term estimates. A long-term analysis using a dynamic framework that accommodates interactions between variables and changes to capital assets (investment new technology), land area and permanent labour supply may produce more definitive results. The results of short-term gross margins assessments can only be indicative of the likely impact of the carbon price on the financial status of the selected vegetable industries.

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[110] Bell, R, Gali, J, Gretton, P and Redmond, R. 2007. The responsiveness of Australian farm performance to changes in irrigation water use and trade. Paper presented to the 51st Annual Conference of the Australian Agricultural and Resource Economics Society, Queenstown, New Zealand. 14-16 February.

6.5 Scenario values

Table 11 presents the values used for critical variables in each of the scenarios. The baseline price for water used in the gross margins is $100/ML.

Table 11: Values of key variables used in vegetable crop gross margins

Crop	Water use (ML/ha)	Pumping cost ($/ML)	Cooling cost ($/ha)	Fertilizer cost ($/ha)	Average yield (t/ha)	High temp yield (t/ha)	Average price ($/t)
Beans	3.0	90	210	530	10.5	7	440
Beetroot	4.0	80	0	700	35	25	180
Broccoli	3.5	90	380	530	7.5	4	2200
Capsicums	4.0	90	300	1350	30	24	1300
Carrot	4.0	90	550	800	55	37	310
Cauliflower	5.0	90	380	650	28	16	820
Sweet corn	5.0	40	0	670	25	17.5	200
Lettuce	3.0	90	600	580	30	15	730

Sources: AusVeg personal communication; AHR estimates; Queensland DAFF and NSW DPI gross margins data

Thompson, T and Zhang, K. 2012. Australian vegetable growing farms: An economic survey 2010-11 and 2011-12. *ABARES Research Report* 12.11, Prepared for Horticulture Australia Limited, Canberra, December

Table 12: Key input values and yield assumptions for vegetable production scenarios

	Scenario	1. Baseline	2. Carbon price	3. Carbon price + efficiencies	4. Carbon price + higher temperatures	5. Severe drought	6. Worst-case
Beans	*Water use*	3 ML/ha	3 ML/ha	3 ML/ha	3 ML/ha	3 ML/ha	3 ML/ha
	Pumping cost	$90/ML	$90/ML	$90/ML	$90/ML	$90/ML	$90/ML
	Cooling cost	$210/ha	$210/ha	$210/ha	$210/ha	$210/ha	$210/ha
	Yield	10.5 tonnes/ha	10.5 tonnes/ha	10.5 tonnes/ha	6.8 tonnes/ha	6.8 tonnes/ha	6.8 tonnes/ha
	Water price	$100/ML	$100/ML	$100/ML	$250/ML	$500/ML	$1500/ML
	Price response				Yes	Yes	Yes
Beetroot	*Water use*	4 ML/ha	4 ML/ha	4 ML/ha	4 ML/ha	4 ML/ha	4 ML/ha
	Pumping cost	$80/ML	$80/ML	$80/ML	$80/ML	$80/ML	$80/ML
	Cooling cost	$0	$0	$0	$0	$0	$0
	Yield	35 tonnes/ha	35 tonnes/ha	35 tonnes/ha	25 tonnes/ha	25 tonnes/ha	25 tonnes/ha
	Water price	$100/ML	$100/ML	$100/ML	$250/ML	$500/ML	$1500/ML
	Price response				Yes	Yes	Yes
Broccoli	*Water use*	3.5ML/ha	3.5ML/ha	3.5ML/ha	3.5ML/ha	3.5ML/ha	3.5ML/ha
	Pumping cost	$90/ML	$90/ML	$90/ML	$90/ML	$90/ML	$90/ML
	Cooling cost	$380/ha	$380/ha	$380/ha	$380/ha	$380/ha	$380/ha
	Yield	7.5 tonnes/ha	7.5 tonnes/ha	7.5 tonnes/ha	4 tonnes/ha	4 tonnes/ha	4 tonnes/ha
	Water price	$100/ML	$100/ML	$100/ML	$250/ML	$500/ML	$1500/ML
	Price response				Yes	Yes	Yes
Capsicums	*Water use*	4 ML/ha	4 ML/ha	4 ML/ha	4 ML/ha	4 ML/ha	4 ML/ha
	Pumping cost	$90/ML	$90/ML	$90/ML	$90/ML	$90/ML	$90/ML
	Cooling cost	$300/ha	$300/ha	$300/ha	$300/ha	$300/ha	$300/ha
	Yield	24 tonnes/ha	30 tonnes/ha	30 tonnes/ha	19.2 tonnes/ha	19.2 tonnes/ha	19.2 tonnes/ha
	Water price	$100/ML	$100/ML	$100/ML	$250/ML	$500/ML	$1500/ML
	Price response				Yes	Yes	Yes
Carrots	*Water use*	4 ML/ha	4 ML/ha	4 ML/ha	4 ML/ha	4 ML/ha	4 ML/ha
	Pumping cost	$90/ML	$90/ML	$90/ML	$90/ML	$90/ML	$90/ML
	Cooling cost	$550/ha	$550/ha	$550/ha	$550/ha	$550/ha	$550/ha
	Yield	55 tonnes/ha	55 tonnes/ha	55 tonnes/ha	37.5 tonnes/ha	37.5 tonnes/ha	37.5 tonnes/ha
	Water price	$100/ML	$100/ML	$100/ML	$250/ML	$500/ML	$1500/ML
	Price response				Yes	Yes	Yes
Cauliflower	*Water use*	5ML/ha	5ML/ha	5ML/ha	5ML/ha	5ML/ha	5ML/ha
	Pumping cost	$90/ML	$90/ML	$90/ML	$90/ML	$90/ML	$90/ML
	Cooling cost	$380/ha	$380/ha	$380/ha	$380/ha	$380/ha	$380/ha
	Yield	28 tonnes/ha	28 tonnes/ha	28 tonnes/ha	16 tonnes/ha	16 tonnes/ha	16 tonnes/ha
	Water price	$100/ML	$100/ML	$100/ML	$250/ML	$500/ML	$1500/ML
	Price response				Yes	Yes	Yes

	Scenario	1. Baseline	2. Carbon price	3. Carbon price + efficiencies	4. Carbon price + higher temperatures	5. Severe drought	6. Worst-case
Sweet corn	*Water use*	5 ML/ha	5 ML/ha	5 ML/ha	5 ML/ha	5 ML/ha	5 ML/ha
	Pumping cost	$40/ML	$40/ML	$40/ML	$40/ML	$40/ML	$40/ML
	Cooling cost	$0	$0	$0	$0	$0	$0
	Yield	25 tonnes/ha	25 tonnes/ha	25 tonnes/ha	17.5 tonnes/ha	17.5 tonnes/ha	17.5 tonnes/ha
	Water price	$100/ML	$100/ML	$100/ML	$250/ML	$500/ML	$1500/ML
	Price response				Yes	Yes	Yes
Lettuce	*Water use*	3ML/ha	3ML/ha	3ML/ha	3ML/ha	3ML/ha	3ML/ha
	Pumping cost	$90/ML	$90/ML	$90/ML	$90/ML	$90/ML	$90/ML
	Cooling cost	$600/ha	$600/ha	$600/ha	$600/ha	$600/ha	$600/ha
	Yield	30 tonnes/ha	30 tonnes/ha	30 tonnes/ha	15 tonnes/ha	15 tonnes/ha	15 tonnes/ha
	Water price	$100/ML	$100/ML	$100/ML	$250/ML	$500/ML	$1500/ML
	Price response				Yes	Yes	Yes

6.6 Economic Impacts for selected crops

Results for the assessments of each vegetable crop under each scenario are presented separately in the following sections with accompanying tables. A number of general findings are presented in an overview at the end.

Figure 36 shows comparative input costs for a typical Australian vegetable farm. The highest cost is labour (21%), and then fertilizer (12%). The cost of electricity is relatively low overall at about 3% but this would vary significantly between farms.

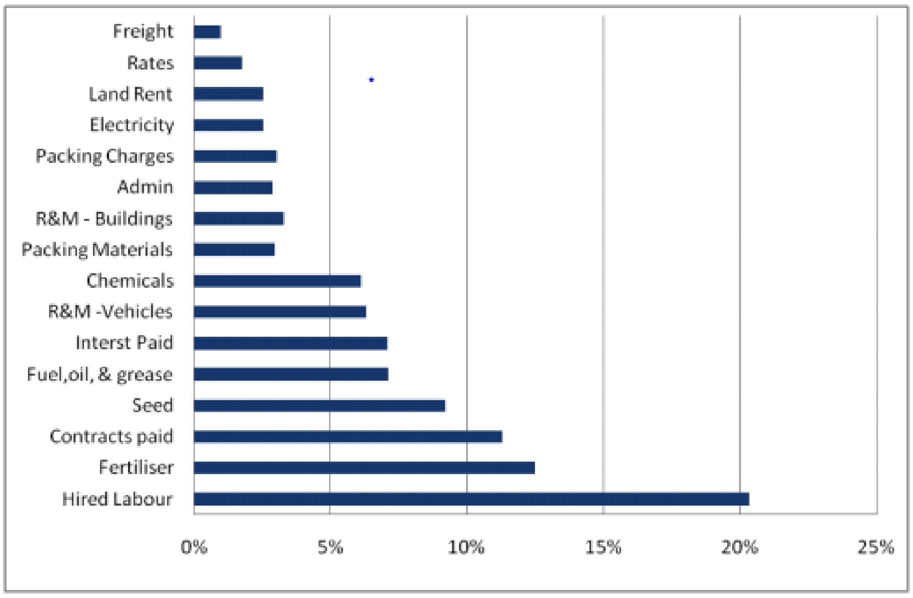

Figure 36. Comparative input costs for an average Australian vegetable farm[111].

6.6.1 Beans

Table 13 presents the gross margins for the six scenarios for bean production. The effect of the carbon price is to reduce the gross margin by 2.1% or almost $50 per hectare. Costs increase by 2.22% as a direct result of the carbon price. If electricity consumption is reduced by 25% for pumping and cooling simultaneously by adoption of efficiency measures, the carbon price is more than offset with the gross margin increasing by 3.48% or $82.56 per hectare. The effect of the carbon price can be fully offset by adoption of measures that would reduce electricity use by 16.75% for pumping, or measures to reduce electricity use by 21.5% for cooling. Achievement of these efficiencies would retain the baseline gross margin. An 8.35% reduction in water use would fully offset the carbon price.

[111] Australian vegetable growing farms: An economic survey 2008-9, ABARE-BRS research report 10.12, November, 2011, p.13

Table 13: **Beans: Predicted impacts of climate on gross margins and costs**

		Baseline	Baseline + carbon price	Baseline + carbon price + efficiencies	Carbon Price + Higher temps	Severe drought	Worst case
Gross margin	$/ha	2374.39	2324.47	2456.95	341.22	-362.13	-2,864.30
Change in gross margin	$/ha		-49.92	82.56	-2033.17	-2736.53	-5,238.69
Change in gross margin	%		-2.10%	3.48%	-85.63%	-115.25%	-220.63%
Change in costs	%		2.22%	-3.68%	18.04%	49.36%	160.79%

Under the carbon price and higher temperatures scenario the baseline gross margin by falls by 83%, with water consumption falling to 2.963ML/ha under an increase in the water price to $250/ML and a 35% decline in yield to 6.8 tonnes per ha. To achieve the baseline gross margin under these production conditions the price of beans would have to increase by 69% to $744 per tonne. Under the severe drought scenario, gross margin is negative, as it is for the worst-case scenario.

6.6.2 Beetroot

Table *14* presents the gross margins for the six scenarios for beetroot. The effect of the carbon price is to reduce the gross margin by 1.93% or $33.28 per hectare. Costs are increased by 0.73%. If electricity consumption is reduced by 25% for pumping through the adoption of efficiency measures, the effect of carbon price on costs is more than offset with the gross margin increasing by 3.19% or $55 per hectare. The effect of the carbon price can be fully offset and the baseline gross margin retained by adoption of measures that would reduce electricity use by 9.4% for pumping. A 4.4% reduction in water use would fully offset the carbon price. Under the carbon price and higher temperatures scenario the gross margin falls to -$691/ha with water consumption falling to 3.95ML/ha, under a water price of $250/ML and a 28% decline in yield to 25 tonnes per ha. Under this scenario, beetroot production is not a viable proposition with variable costs exceeding revenue by 15%. To achieve the baseline gross margin under these production conditions the price of beetroot would have to increase by 54% to $277 per tonne. The severe drought and worst-case scenarios also generate negative gross margins under the influence the higher water prices coupled with reduced yields.

Table *14*: **Beetroot: Predicted impacts of climate on gross margins and costs**

		Baseline	Baseline + carbon price	Baseline + carbon price + efficiencies	Carbon Price + Higher temps	Severe drought	Worst case
Gross margin	$/ha	1725.76	1692.48	1780.80	-690.67	-1629.39	-4,970.27
Change in gross margin	$/ha		-33.28	55.04	-2416.43	-3355.15	-6,696.03
Change in gross margin	%		-1.93%	3.19%	-140.02%	-194.42%	-388.00%
Change in costs	%		0.73%	-1.20%	13.48%	34.00%	107.03%

6.6.3 Broccoli

Table 15 presents gross margins for the six scenarios for broccoli. The effect of the carbon price is to reduce the gross margin by 1.53% or $72 per hectare. Costs are increased by 0.61% as a consequence of the carbon price. If electricity consumption is reduced by 25% for pumping and cooling simultaneously through adoption of efficiency measures, the effect of carbon price on costs is more than offset with the gross margin increasing by 1% or by $119 per hectare. The effect of the carbon price can be fully offset and the baseline gross margin retained by adoption of measures that would reduce electricity use by 21% for pumping or measures to reduce use by 17% for cooling. A 10.36% reduction in water use would fully offset the carbon price.

Table 15: **Broccoli: Predicted impacts of climate on gross margins and costs**

		Baseline	Baseline + carbon price	Baseline + carbon price + efficiencies	Carbon Price + Higher temps	Severe drought	Worst case
Gross margin	$/ha	4721.76	4649.48	4841.30	-3364.52	-4185.10	-7,104.28
Change in gross margin	$/ha		-72.28	119.54	-8086.28	-8906.86	-11,826.04
Change in gross margin	%		-1.53%	2.53%	-171.26%	-188.63%	-250.46%
Change in costs	%		0.61%	-1.01%	3.28%	10.25%	35.03%

The carbon price and higher temperatures scenario produces a negative gross margin, largely associated with the 47% reduction in yield and revenue. Costs are 4% higher than in the baseline gross margin, associated with the higher water price of $250/ML. To achieve the baseline gross margin under these production conditions the price of broccoli would have to almost double to more than $4200 per tonne. For the severe drought and worst-case scenarios the gross margins are negative, a result of the reduced revenues due to heat-affected yields and higher water prices.

6.6.4 Capsicums

Table 16 presents the gross margins for the six scenarios for capsicums. The effect of the carbon price is to reduce the gross margin by 1.2% or $68.64 per hectare. Costs are increased by 0.27% due to the impact of the carbon price on electricity prices. If electricity consumption is reduced by 25% for pumping and cooling simultaneously through adoption of efficiency measures, the effect of carbon price on costs is more than offset with the gross margin increasing by 1.98% or $113 per hectare. The effect of the carbon price can be fully offset and the baseline gross margin retained by adoption of measures that would reduce electricity use by 17% for pumping or measures to reduce electricity use by 21% for cooling.

A reduction of 8.6% in water use would fully offset the carbon price. The carbon price and higher temperature scenario produces a negative gross margin associated with an increase in the water price to $250/ML and a 20% decline in yield to 19.2 tonnes per ha. To achieve the baseline gross margin under these production conditions the price of capsicums would have to increase by 27% to $1671 per tonne. For the severe drought and the worst-case scenarios the gross margin is negative.

Table 16: Capsicums: Predicted impacts of climate on gross margins and costs

		Baseline	Baseline + carbon price	Baseline + carbon price + efficiencies	Carbon Price + Higher temps	Severe drought	Worst case
Gross margin	$/ha	5732.74	5664.10	5846.26	-1152.26	-2090.06	-5,426.28
Change in gross margin	$/ha		-68.64	113.52	-6885.00	-7822.80	-11,159.02
Change in gross margin	%		-1.20%	1.98%	-120.10%	-136.46%	-194.65%
Change in costs	%		0.27%	-0.44%	2.27%	5.91%	18.86%

6.6.5 Carrots

Table 17 presents the gross margins for the six scenarios for carrots. The effect of the carbon price is to reduce the gross margin by 6.3% or almost $95 per hectare. Costs are increased by 0.61% due to the carbon price impacts on electricity prices. If electricity consumption is reduced by 25% for pumping and cooling simultaneously through the adoption of efficiency measures, the effect of carbon price on costs is more than offset with the gross margin increasing by 10.4% or $157 per hectare. The effect of the carbon price can be fully offset and the baseline gross margin retained by adoption of measures that would reduce electricity use by 24% for pumping or measures to reduce use by 16% for cooling. A reduction in water use by 11.9% would fully offset the carbon price.

The carbon price and higher temperature scenario produces a negative gross margin, associated with a water price of $250/ML and a 32% decline in yield to 37.5 tonnes per ha. Water consumption falls to 3.95ML/ha. To achieve the baseline gross margin under these production conditions the price of carrots would have to increase by 51% to $470 per tonne. For the severe drought and worst-case scenarios the gross margins are negative, associated with lower yields and the very high water prices, reflecting the scarcity of irrigation water. Costs under these scenarios are 9% and 31% higher, respectively, than costs in the baseline.

Table 17: Carrots: Predicted impacts of climate on gross margins and costs

		Baseline	Baseline + carbon price	Baseline + carbon price + efficiencies	Carbon Price + Higher temps	Severe drought	Worst case
Gross margin	$/ha	1505.99	1411.35	1662.51	-4403.05	-5340.85	-8,677.07
Change in gross margin	$/ha		-94.64	156.52	-5909.04	-6846.84	-10,183.06
Change in gross margin	%		-6.28%	10.39%	-392.37%	-454.64%	-676.17%
Change in costs	%		0.61%	-1.01%	3.11%	9.15%	30.61%

6.6.6 Cauliflower

Table 17 presents the gross margins for the six scenarios for cauliflower. The effect of the carbon price is to reduce the gross margin by 0.95% or $86.32 per hectare. Costs are increased by 0.62%. If electricity consumption is reduced by 25% for pumping and cooling simultaneously through the adoption of efficiency measures, the effect of the carbon price on costs is more than offset with the gross margin increasing by 1.57% or $142.76 per hectare. The effect of the carbon price can be fully offset and the baseline gross margin retained by adoption of measures that would reduce electricity use by 17% for pumping or alternatively measures to reduce electricity use for cooling by 21%. A reduction of 8.7% in water use would fully offset the carbon price.

Table 18: Cauliflower: Predicted impacts of climate on gross margins and costs

		Baseline	Baseline + carbon price	Baseline + carbon price + efficiencies	Carbon Price + Higher temps	Severe drought	Worst case
Gross margin	$/ha	9096.71	9010.39	9239.47	-1378.06	-2550.32	-6720.58
Change in gross margin	$/ha		-86.32	142.76	-10474.78	-11647.03	-15817.29
Change in gross margin	%		-0.95%	1.57%	-115.15%	-128.04%	-173.88%
Change in costs	%		0.62%	-1.03%	4.58%	13.03%	43.12%

The carbon price and higher temperatures scenario produces a negative gross margin, associated with a water price of $250/ML and a 43% decline in yield to 1454 cartons per ha (or 16 tonnes/ha). The severe drought and worst-case scenarios generate very large negative gross margins.

6.6.7 Sweet corn

Table 19 presents the gross margins for the six scenarios for sweet corn. The effect of the carbon price is to reduce the gross margin by 0.79% or $21 per hectare. Costs are increased by 0.88% as a result of the carbon price. If electricity consumption for irrigation water pumping is reduced by 25% through the adoption of efficiency measures, the effect of the carbon price on costs is more than offset with the gross margin increasing by 1.3% or $34.40 per hectare. The effect of the carbon price can be fully offset and the baseline gross margin retained by adoption of measures that would reduce electricity use by 9.4% for pumping. A 2.9% reduction in water use would fully offset the carbon price.

Table 19: Sweet corn: Predicted impacts of climate on gross margins and costs

		Baseline	Baseline + carbon price	Baseline + carbon price + efficiencies	Carbon Price + Higher temps	Severe drought	Worst case
Gross margin	$/ha	2632.41	2611.61	2666.81	379.92	-798.06	-$4,991.23
Change in gross margin	$/ha		-20.80	34.40	-2252.49	-3430.47	-$7,623.64
Change in gross margin	%		-0.79%	1.31%	-85.57%	-130.32%	-289.61%
Change in costs	%		0.88%	-1.45%	31.78%	81.54%	258.64%

Under the carbon price and higher temperatures scenario with the water price at $250/ML and a 30% decline in yield to 17.5 tonnes per ha, water consumption falls to 4.938ML/ha and the gross margin is almost 86% less than the baseline gross margin. To achieve the baseline gross margin under these production conditions the price of sweet corn would have to increase by 64% to almost $329 per tonne. For the severe drought and worst-case scenarios the gross margins are negative, well below the baseline level.

6.6.8 Lettuce

Table 20 presents the gross margins for the six scenarios for lettuce. The effect of the carbon price is to reduce the gross margin by 1.17% or $90 per hectare. Costs are increased by 0.64% as a consequence of the carbon price. If electricity consumption is reduced by 25% for pumping and cooling simultaneously through the adoption of efficiency measures, the effect of carbon price on costs is more than offset with the gross margin increasing by 1.94% or almost $150 per hectare. The effect of the carbon price can be fully offset and the baseline gross margin retained by adoption of measures that would reduce electricity use by 30% for pumping or by adoption of measures to reduce electricity use for cooling by 14%. A reduction of 15% in water use would fully offset the carbon price and retain the baseline gross margin.

Table 20: Lettuce: Predicted impacts of climate on gross margins and costs

		Baseline	Baseline + carbon price	Baseline + carbon price + efficiencies	Carbon Price + Higher temps	Severe drought	Worst case
Gross margin	$/ha	7707.15	7616.67	7856.79	-3439.08	-4142.43	-$6,644.59
Change in gross margin	$/ha		-90.48	149.64	-11146.23	-11849.58	-$14,351.74
Change in gross margin	%		-1.17%	1.94%	-144.62%	-153.75%	-186.21%
Change in costs	%		0.64%	-1.05%	1.38%	6.34%	23.97%

The carbon price and higher temperatures scenario produces a negative gross margin, with water consumption falling to 2.96ML/ha, associated with the water price of $250/ML and a 50% decline in yield to 15 tonnes per ha. To achieve the baseline gross margin under these production conditions the on farm price of lettuce would have to double to almost $7.40/carton (equivalent $2400/tonne). The severe drought and the worst-case scenarios produce negative gross margin due to the 50% yield reduction associated with higher temperatures.

6.7 Overview of economic impacts

Table 21 presents a summary of the changes in gross margins for eight vegetable crops analysed, and for the various conditions defined for the six scenarios. The carbon price affects the cost of power for water pumping and post-harvest cooling. The change in the gross margin ranges from a low of 0.8% for sweet corn to more than 6% for carrots. Sweet corn does not require post-harvest cooling, while cooling costs for carrots are relatively high, reflecting the high yield (55 tonnes/ha) and the relatively low gross margin.

The simulated adoption of energy-use efficiencies for water pumping and product cooling that reduce electricity consumption by 25% resulted in increases to gross margins by more than the impact of the carbon price for all vegetable crops. The costs of implementing such efficiencies were not considered nor were specific technologies or changed practices identified.

Table 21: Predicted impacts of carbon price and other changes on vegetable crop gross margins

Crop	Baseline Gross Margin ($/ha)	Change in gross margin due to carbon price (%)	Impact of electricity use efficiencies on gross margin (%)	Impact of higher temperatures (%)	Impact of severe drought (%)	Worst case
Beans	2374.39	-2.10%	3.48%	-85.63%	-115.25%	-220.63%
Beetroot	1725.76	-1.93%	3.19%	-140.02%	-194.42%	-388.00%
Broccoli	4721.76	-1.53%	2.53%	-171.26%	-188.63%	-250.46%
Capsicums	5732.74	-1.20%	1.98%	-120.10%	-136.46%	-194.65%
Carrots	1505.99	-6.28%	10.39%	-392.37%	-454.64%	-676.17%
Cauliflower	9096.71	-0.95%	1.57%	-115.15%	-128.04%	-173.88%
Sweet Corn	2632.41	-0.79%	6.06%	-85.57%	-130.32%	-289.61%
Lettuce	7707.15	-1.17%	1.94%	-144.62%	-153.75%	-186.21%

The high temperatures scenario is characterised by moderate drought conditions with temperatures moderately higher than average, crop yields ranging from 50% to 20% less than average yields and the price of irrigation water 2.5 times the baseline price of $100/ML. Commodity prices are the same as in the baseline scenario. Input usage and costs were unchanged from the baseline with one exception – water use was reduced in line with its price elasticity of demand. This scenario generated significant declines in gross margins for all crops with none exhibiting a positive gross margin. In reality, shortages in supply would force prices up, so the impacts on gross margins would likely be less than is modelled here. The predicted impacts on costs (**Table 22**) gives a more reliable indication.

For the severe drought scenario, production and market conditions are very similar to those of the higher temperatures scenario but the price of water is much higher at $500/ML. Under these conditions the gross margin is negative for all crops. The results are the same for the worst-case scenario for all crops.

The data in **Table 22** shows the impact of the carbon price on total costs for each vegetable crop. These data reveal a consistent pattern with costs increasing on average by 0.82% due to the carbon price. The impact of electricity-use efficiencies of 25% for both pumping and cooling reduces costs by just over 2% on average, ranging from 1% for broccoli to almost 7% for sweet corn. Under the higher temperatures and severe drought scenarios costs increase on average by 10% and 26%, respectively. The higher temperatures and severe drought scenarios incur significantly higher water prices and much lower yields than under the baseline conditions.

Table 22: Predicted impacts of carbon price and other changes on total production

Crop	Baseline total costs ($/ha)	Impact of change on total costs (%)				
		Carbon price	Electricity use efficiencies	Higher temperatures	Severe drought	Worst case
Beans	2,245.61	2.22%	-3.68%	18.04%	49.36%	160.79%
Beetroot	4,574.24	0.73%	-1.20%	13.48%	34.00%	107.03%
Broccoli	11,778.24	0.61%	-1.01%	3.28%	10.25%	35.03%
Capsicums	25,767.26	0.27%	-0.44%	2.27%	5.91%	18.86%
Carrots	15,544.01	0.61%	-1.01%	3.11%	9.15%	30.61%
Cauliflower	13,863.29	0.62%	-1.03%	4.58%	13.03%	43.12%
Sweet Corn	2,367.59	0.88%	-6.73%	31.78%	81.54%	258.64%
Lettuce	14,192.85	0.64%	-1.05%	1.38%	6.34%	23.97%
Average		0.82%	-2.02%	9.74%	26.20%	84.76%

7 Strategies to deal with climate change

Australia's vegetable growers already have to cope with a harsh and variable environment, and have shown time and again that they are capable of rising to the challenge of running viable vegetable farming operations in the face of these challenges.

Increased climate variability and longer-term climate change will bring increasing challenges to growers, and also some potential benefits.

We have already begun to experience the changes that have been predicted for the next five years. These, and changes predicted for the coming 20 years are outlined in section 2.6 of this review. There will be changes in average temperatures and more frequent extreme events. The frost window will widen, and rainfall patterns will change. Some areas will become marginal for vegetable production and others areas will become more suitable (section 2.7).

There will be some beneficial effects from higher CO_2 levels on plant growth rates, and reduced water use due to reduced plant water-use. Generally higher temperatures will impact on greenhouse production, increasing cooling costs in some areas, but also reducing heating costs in other regions. The vegetable industry will need to address these changes if it is to remain viable.

There are two main ways in which the vegetable industry can address climate variability in the short term and climate change in the longer term:

- Adapt farming practices to changes in weather patterns, which have already occurred and are predicted to occur in the future.
- Reduce emissions of greenhouse gases from farms directly and as a result of farming activities.

The former approach is generally referred to as **adaptation**, and the latter as **mitigation.**

7.1 Adaptation options

Adapting farming practices, and the industry more generally, to climate variability and change is described in Figure 37. The climate adaptation group at CSIRO led by Dr Mark Howden has led the way in the thinking about how adaption to climate change will work in relation to agricultural industries, including the vegetable industry.

There are three levels to adaptation, and in time the benefits that are likely to be gained from activities at each level will diminish. It's like the law of diminishing returns in economics.

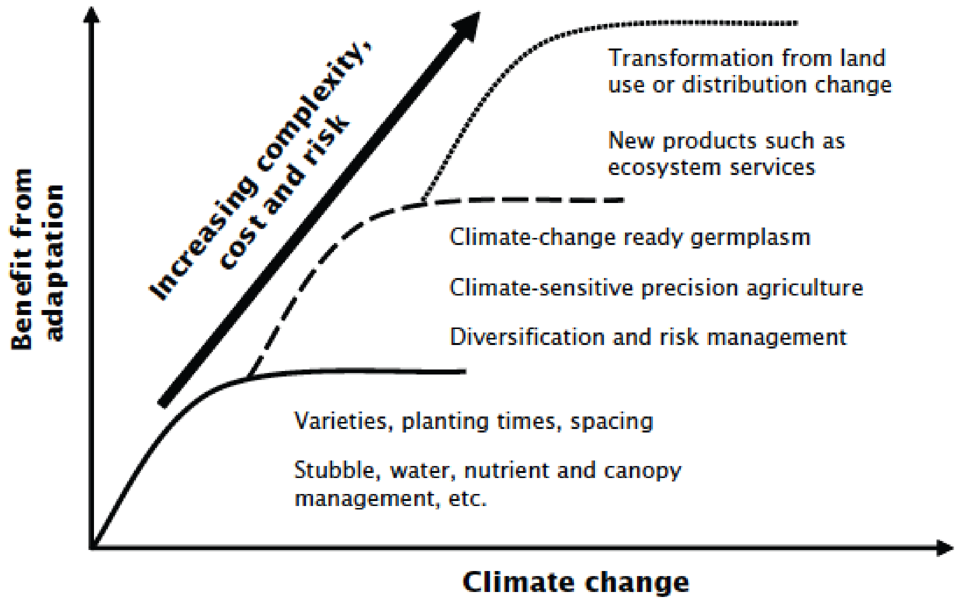

Figure 37. The potential benefits from different levels of adaptation with increasing climate change ranging from within-system responses to higher-level transformational changes[112].

Adaptation to climate change with respect to vegetable production can be thought about in three stages:

> **Stage 1**: These are the most immediate changes and they are similar to adapting to normal weather variability. These changes include varieties, new planting schedules, nutrient and irrigation management.
>
> **Stage 2**: These changes will cost more, and require longer to develop, but are likely to provide solutions once the stage 1 adaptations reach their maximum impact. Strategies could include new varieties bred specifically for climate change, precision agriculture and diversification of production enterprises.
>
> **Stage 3:** Transformational changes – things we may not yet have thought about, new products, new ways of producing crops, ecological services.

At this stage of the response of vegetable production to climate change, we are mainly focussed on stage 1, but it is worthwhile for the industry to give consideration to the other stages as well, especially in the formulation of a research and development plan, which is part of this review.

Horticulture Australia has recently issued a call for research proposals on transformational research (March, 2013) and up to $12.5M in funding is available over a five-year period for co-investment with research agencies or institutes in transformational research themes critical to the success of the horticultural industry in 2035.

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[112] Stokes and Howden (2011) Adapting agriculture to climate change in Cleugh, H. et al. (2011) Climate change: Science and solutions for Australia. CSIRO.

The following areas have been identified in this review as likely to have the most immediate impact on alleviating adverse effects of increased climate variability and longer-term climate change in the vegetable industry.

7.1.1 Varieties: Breeding or selecting varieties that will grow in the changed climate

The sensitivity of individual crops and varieties to temperature is likely to be the most important single direct effect of climate change and increased variability on the vegetable industry. The predicted changes in average temperatures for six regions have been presented in section 2.7. In addition, there is the expected increase in the variability of extreme weather events including heatwaves. These combined effects are likely to mean major changes in where vegetables can be grown and how growers deal with extreme events.

There may be a view among growers that impacts of changing temperature profiles of our growing regions can be countered by seed companies breeding new varieties with wider optimal temperature ranges or better heat tolerance.

There will be some capacity available within current and future varieties to adapt to some of the predicted changes in temperature, but this capacity will not be great. Where crops are already growing at the upper or lower end of the acceptable temperature range, there is little capacity available within the current range of varieties to extend these limits. The major vegetable breeding companies have not indicated that climate change is currently a major driver for investment in extending the temperature range of vegetable crop varieties.

It is also possible there will be interactions between higher temperatures and higher CO_2 levels on the way vegetable varieties respond to a more variable climate, and this could be a potential area for future research. Some useful data may come from greenhouse research, where vegetable crops such as tomatoes, capsicums and cucumbers are commonly grown in glasshouses under CO_2 enrichment, especially in Europe.

In Australia we do not breed many of our vegetable species, with the exception of lettuce by Enza, broccoli by Clause and some cooperative breeding by Rijk Zwaan. To determine what are the actual tolerances for genotypes that suit the local markets in Australia, it may be more prudent to screen varieties under hot conditions or under passive heat tunnels[113]. Such assessments are already underway for some of Australia's broad acre crops, e.g. wheat.

[113] Daniel Tan, pers. comm.

7.1.1.1 *Most likely crops for which variety selection will be a solution*

Capsicums: AVRDC is currently breeding for heat tolerance, but new varieties will be in the long term.

Beans: Breeding is underway for heat and drought tolerance – long-term solution.

Lettuce: Monsanto and Clause are both breeding for heat tolerance. Breeding for cold tolerance is also underway for southern Australia and New Zealand.

Cauliflower: Breeding is active, using genetics from India for heat tolerance. Long-day overwintering types are available in Europe.

Broccoli: There is already a wide range of varieties available for different climatic zones. Sakata seeds and Clause are both active in this area.

Babyleaf spinach: There are active breeding programs in Europe and the US for babyleaf spinach lines, which span a wide range of temperature. The main problem is with heat tolerance; cold is already well covered. There are likely to be problems in areas such as Stanthorpe, SE Qld for summer production.

Rocket: Arugula and European wild rocket types are available, which should cover the climatic requirements in most areas.

7.1.1.2 *Crops where variety / germplasm solutions are unlikely*

Carrots: The temperature range is already wide for F1 hybrid varieties.

Sweet corn: There is potential to breed varieties with better cold tolerance for seed germination in cold wet soils in spring and heat tolerance but breeding is not active in this area.

Beetroot: high temperature cut-off of 27^{o}C is likely to be a significant problem and no breeding program has been identified to address this issue.

7.1.2 Seed industry comments

Enza Zaden. In lettuce, the issue of loss of quality and tipburn is more of an issue with spikes in temperature. Growers select varieties to suit their climate (winter varieties in winter; summer varieties in summer) so tipburn can be an issue when a spike in temperature from 20°C to 30°C occurs in late winter or 30°C to 38°C in summer. Some growers are already pushing the boundaries in regards to the colder weather because supermarkets and processors require lettuce all year round, and to fulfil those contracts those growers need to produce in the extreme cold.

Enza Zarden is breeding for the winter slot in Australia and New Zealand, and working on new varieties for the more extreme colder climates. They are also breeding for the warmest slots in Australia. Within this slot they are also breeding for South America, so in effect breeding for warmer and more humid climates than where lettuce is currently grown in Australia. The potential is for lettuce production to expand into other growing slots or into new growing areas. As demand increases worldwide for fast-food, which usually includes lettuce, more lettuce will need to be grown in areas not ideal for lettuce growing, often in countries that are tropical and sub-tropical.

In summary, Enza Zarden is breeding in response to economics and developing markets, but this may also help with new varieties adapted to a warmer climate. (***Steve Mitchell*** PhD, Lettuce Plant Breeder (Australia & New Zealand). Enza Zaden Australia Pty Ltd, Australia.)

Clause Pacific. A key focus of the Clause broccoli breeding and Vilmorin lettuce selection programs is for varieties to be adapted to the particularly variable climatic conditions of Australia, with a specific focus on heat tolerance.

The HM-Clause brassica breeding program is executed in both Europe and Australia, with the latter offering counter-season production for faster variety creation, but also an excellent selection zone for heat tolerance during the summer periods in Victoria. In recent years the summer selection program in Australia has increased fourfold on both parental lines and hybrids for broccoli in an attempt to develop higher levels of heat tolerance, making varieties adaptable for the global markets as well as Australia. The high temperatures experienced in Victoria's summer would be equal to that of any other broccoli-producing markets globally, providing the flexibility to market anywhere, which is also true for both cauliflower and lettuce varieties, which are being selected under the same conditions. Changes in critical temperatures for the new broccoli varieties are expected to vary only slightly from those presented in this review, which should significantly improve the level of adaptability. (***Daniel Gleeson***, Director, Clause Pacific.)

Monsanto (De Ruiter, Seminis). Monsanto develops varieties with a wide range of consumer, agronomic and disease traits. The ability for a plant to perform to commercial standards under hot conditions can be measured in a range of ways, e.g. fruit-setting ability in tomato crops or tipburn tolerance in leafy crops. Temperature is only one of many environmental factors that can influence the performance of varieties. Because there are multiple variables we test varieties under local Australian commercial growing conditions. Monsanto will assess a range of traits based on what they consider important to the Australian market. Monsanto has the capacity to develop their own genetics to suit a range of production environments from the open field to low-tech plastic tunnels and high-tech glasshouse structures, which they believe gives them capacity to combine vegetable quality with agronomic needs. (***Troy Mulcahy,*** ANZ Technology Development Lead Vegetable Seeds. Monsanto Australia and New Zealand.)

Rijk Zwaan. In today's global market place, production will move where it is the most cost efficient providing there are no quarantine barriers. This movement can be geographical and in time (e.g. to a cooler time of the year). Genetic adaptation to extreme growing conditions will only be done when there is no other solution. For example, in the seventies due to the first oil crisis there was demand for cold tolerant greenhouse tomato varieties however it turned to be much easier to increase yield thereby reducing the required energy input per kg of product. Growing tomatoes at low temperatures was followed by a suite of other issues such as botrytis, poor return on CO_2 enrichment. Genetic adaptation of the crop to high temperatures will only solve part of the problem. Faster pest reproduction cycles will increase pest pressure as well as potential to transmit viral diseases.

Rijk Zwaan does include continuous selection for climate extremes in their breeding programs. "While we do have a strategy for climate change, we do not see this as relevant for our high input target markets. For field crops with large acreages and for important local supply chains, and I think the challenge is much clearer. Even so, you would still have to ask the question if a drought tolerant variety will also be the best producing variety in a normal or wet year". (***Arie Baeldie***, Rijk Zwaan Australia).

7.1.2.1 Example of a variety x CO_2 x temperature interaction in babyleaf spinach

There has been some recent research on baby-leaf spinach, which shows a very interesting interaction between CO_2, concentration and growing temperature. Two baby-leaf spinach varieties, Donkey (slow growing) and Racoon (fast growing), were grown at two CO_2 concentrations, 400 ppm (ambient) and 640 ppm, over three temperature regimes, 22, 26 and 30^{o}C (Figure 38). Both varieties grew best at 22^{o}C and progressively worse at 26 and 30^{o}C. The higher CO_2 concentration has a significant positive impact on growth at the two lower temperatures, and in the faster-growing variety, Racoon, the elevated CO_2 counteracted the adverse effect of higher temperature on growth at 26^{o}C but was not able to do the same at 30°C. This type of study shows the critical impact of temperature on the growth of cool-season leafy crops such as spinach and the complicated interactions that occur between variety type and the direct effects of higher CO_2 levels.

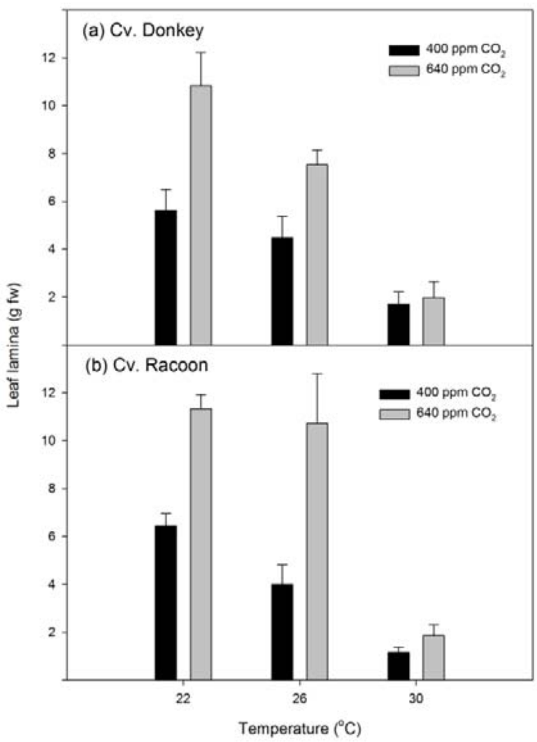

Figure 38. Baby leaf spinach varieties Donkey and Racoon (Rijk Zwaan) were grown at elevated and ambient CO2 concentrations at three different temperature regimes[114].

[114] Source (Jann Conroy, pers. comm.)

7.1.3 Move regions or crops

A strategy that is open to growers is to move to regions with a more favourable climate. This is clearly a major undertaking in terms of infrastructure and set-up costs in the new regions.

The predicted impacts of climate variability and change on current growing regions have been examined in detail in section 2.7 and the main issues that have been identified as limitations to current cropping pattern are an increase the variability or weather, more heatwaves and a larger frost window. These findings are common across all scenarios, and it is doubtful that simply moving regions will do much to alleviate these problems.

In general coastal areas will be less affected by climate change, but the land values of these regions will be higher than inland areas. The coastal impact is evident in predictions about Tasmania where smaller than average increases in temperature expected. Refer to predictions for Devonport.

A proper assessment of all potential new regions for the production of specific crops is a major undertaking, and beyond the scope of this review.

Case study: Australian Wine Industry.

The wine industry is already on the lookout for cooler climates. Treasury Wine Estates, the world's second-largest listed wine company, is seeking out vineyards in cooler regions in preference to ones in warmer areas as climate change starts to shift growing seasons.

"As the world heats, Tasmania is very well positioned because of the cooler climate. We've got out of places like the Hunter; in the longer term I think it will be hot and dry and expensive." (Treasury Wine Estates CEO David Dearie, SMH April 12, 2013).

7.1.4 Water for irrigation: Availability and cost

Water management and irrigation is an area that will potentially become more important for the vegetable industry in the future, but this may be more due to issues related to water and irrigation, than simply to a lack or oversupply of water.

For example, areas reliant on local supply appear to be more vulnerable to shortages e.g. the Lockyer Valley. When a region is part of a larger scheme e.g. Murrumbidgee, then water can be purchased during droughts, and so water security is greater. The cost of water during droughts however may mean production is not economically viable. Refer to section 6 for an analysis of drought on input costs and gross margins.

The vegetable industry is already an efficient user of irrigation water. Water saving application methods such as trickle irrigation and the use of sophisticated soil moisture monitoring equipment have made vegetable producers efficient water users.

Vegetables use about 3.5 ML/ha to produce a crop, one of the lowest rates of all irrigated agriculture (Figure 39) and use only 4% of Australia's irrigation water (Table 23).

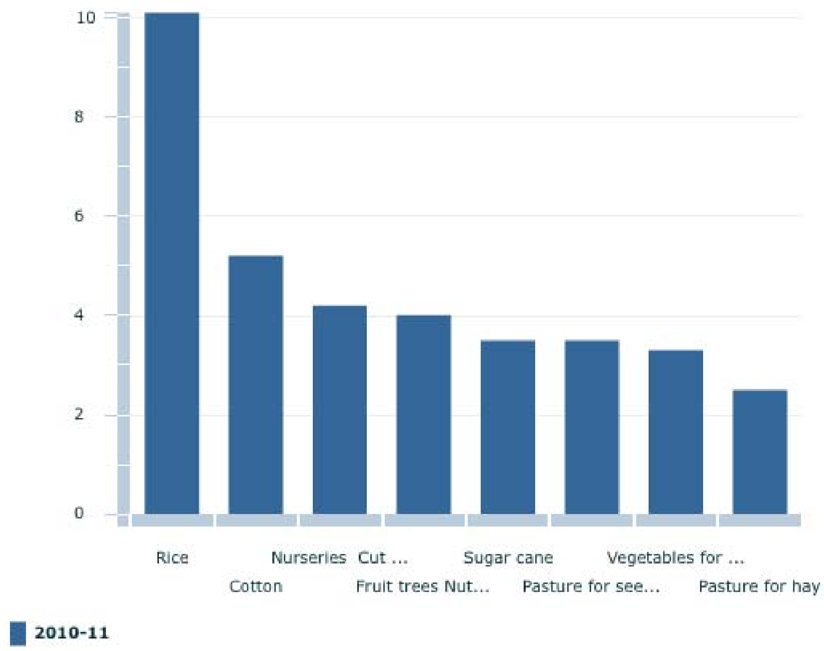

Figure 39. Irrigation water use per hectare for crop types in Australia. Source: ABS 2011

The financial returns per ML of water applied is higher for vegetables than any other agricultural crop grouping (Figure 40), which means that vegetable growers are in a stronger position compared to other industries when water prices rise in times of drought.

Water prices in Australia rose to $1500 per ML during the drought in the late 2000s. Vegetables have a gross value of production per ML of more than $3000 per ML across all irrigated vegetables (Table 23), and while this puts the vegetable industry in a better position relative to all other water users, high water prices remain a major threat to the financial viability of vegetable farming in Australia. The economic analysis covered in section 6 identifies major increases in the cost of water in severe droughts as being the greatest threat to the economic viability of vegetable production, based on current input costs and returns.

Table 23. Water use and gross value of production for irrigated agriculture, Australia (ABS 2004) [115]

	Net water use		Irrigated area		Gross value per ML	
	1996/97 GL	2000/01 GL	1996/97 '000 ha	2000/01 '000 ha	1996/97 $/ML	2000/01 $/ML
Vegetables	635	556	89	116	1 762	3 270
Grapes	649	729	70	133	945	1859
Fruit	704	803	82	116	1459	1213
Dairy	–	2834	–	–	–	529
Cotton	1 841	2 908	315	437	613	420
Livestock, pasture, grains and other agriculture	8 795	8 403	1 175	1 403	289	373
Sugar	1236	1311	173	211	418	217
Rice	1 643	1 951	152	179	189	179
Total	**15 503**	**16 660**	**2 057**	**2 506**	–	–

[115] Hickey, Hoogers, Singh, Christen, Henderson, Ashcroft, Top, O'Donnell, Sylvia & Hoffmann (2006) Maximising returns from water in the Australian vegetable industry: National report. AusVeg

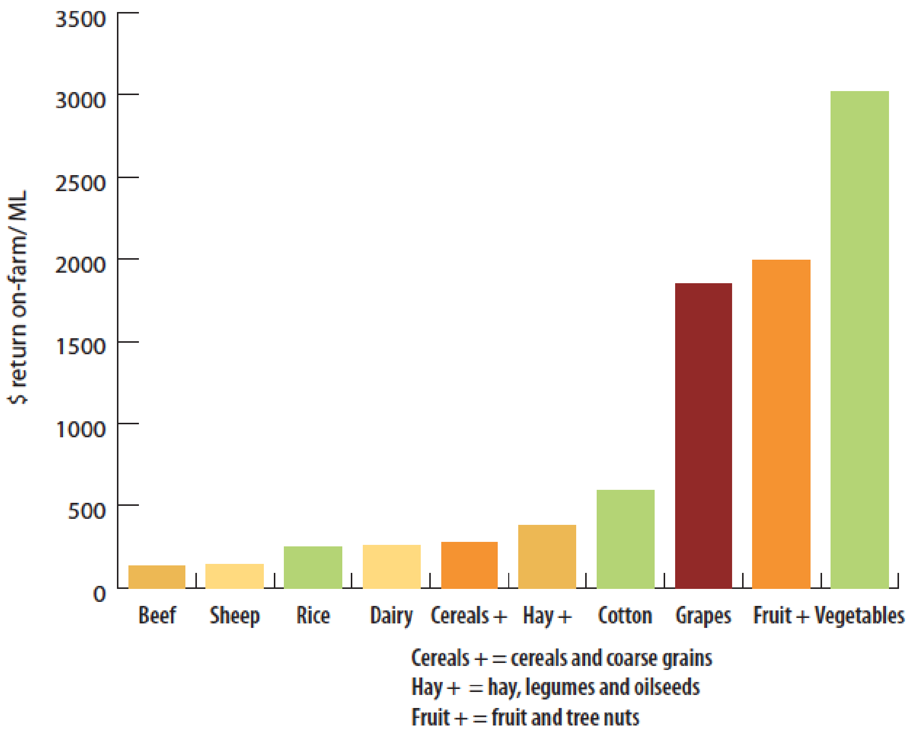

Figure 40. Revenue ($/ML) from land use and volume of water, Murrumbidgee-Murray-Goulburn regions 2000/1[116].

7.1.5 Use of Irrigation to manage frost and high temperature spikes

There is an opportunity in using irrigation as a tool to manage temperature extremes in vegetable crops. Temperature stress is likely to occur either as:

- high temperature spikes or heatwaves; or
- frosts.

High temperature spikes: there is the potential to use overhead solid-set irrigation or hand-shift sprinkler irrigation to reduce the temperature of foliage, flowers or fruit during high temperature extremes. It would be possible to use travelling irrigators or centre pivots for the same use.

Consideration should be given by growers to retaining the capacity for using sprinklers for temperature mitigation. In lettuce production for example, it is common practice to install both trickle- and solid-set sprinkler irrigation on the same crop. The solid set is used to keep the soil uniformly moist for good crop establishment, especially on direct-seeded crops, and then switch to trickle irrigation for the main growing cycle to maximise water use efficiency and water availability to the plant.

Frost control: The likely impact of frost on the vegetable industry is high, especially if climate change increases the incidence or severity of frost occurring on frost-sensitive crops,

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[116] Hickey, Hoogers, Singh, Christen, Henderson, Ashcroft, Top, O'Donnell, Sylvia & Hoffmann (2006) Maximising returns from water in the Australian vegetable industry: National report. AusVeg

or at frost-sensitive stages of development. If the predicted increases in the variability of the climate occur, especially in the frequency of extreme hot and cold spells, then frost is likely to become a more important issue than is currently the case.

The potential economic impact of frost is much higher than changes in the average temperatures that will occur in growing regions might seem to suggest. Average temperature changes will be gradual and there will be time to change crop species or varieties, or even move to new regions over time if required; however a severe frost can have a devastating effect on the profitability of a farming operation.

The extent of this potential loss depends on the length of the growing season. Crops with a shorter growing season such as lettuce and other leafy salad vegetables are likely to be least affected (4-8 weeks). Longer-term crops such as brassicas, carrots, beetroot and sweet corn are likely to be more affected, although the most frost-sensitive stages are usually in the germination and establishment phases. (Refer to Table 5 on crop temperature sensitivity). Vegetable growers are in a strong position in relation to managing frost because they always have the opportunity to irrigate crops, especially with overhead sprinkler irrigation, which is a powerful tool in the minimisation of frost damage.

7.1.6 Salinity

A significant threat to the vegetable industry is the salinization of irrigation water in times of drought. The impact of drought on the quality of irrigation water may mean that it is unsuitable for use on salt-sensitive crops. Table 24 shows the sensitivity of major vegetable crops to salinity. In Australia the vegetable-producing areas most at risk from higher salinity in response to drought include:

- Qld: The Lockyer Valley, Bowen
- Vic: Werribee, Vic using recycled water for irrigating vegetables
- WA: Perth, Manjimup, Pemberton
- SA: Virginia / Murray Bridge

A recent review is available on the impact of recycled water from sewage for crop irrigation[117].

[117] Jankovich, M., Stevens, D. et al. (2004). Impacts on crop quality from irrigation with water reclaimed from sewage Arris.

Table 24. Vegetable crops water salinity tolerance (ECw). Table indicates the yield reductions that could be expected when various vegetable crops are irrigated with saline water.

Vegetable crop	No yield reduction EC_w (dS/m)	10% yield reduction EC_w (dS/m)
Zucchini	3.1	3.8
Garden beet	2.7	3.4
Broccoli	1.9	2.6
Cucumber	1.7	2.2
Tomato	1.7	1.9
Cantaloupe/rockmelon	1.4	2.4
Watermelon	1.3	na
Spinach	1.3	2.2
Cabbage	1.2	1.9
Celery	1.2	2.2
Broad bean	1.1	1.8
Potato	1.1	1.7
Sweet potato	1.0	1.6
Capsicum	1.0	1.5
Sweet corn	1.0	1.7
Lettuce	0.9	1.4
Onion	0.8	1.2
Eggplant	0.7	1.6
Carrot	0.7	1.2
Beans	0.7	1.0
Radish	0.7	0.9
Turnip	0.6	1.3

7.1.7 Irrigation case study: Lettuce and broccoli: sprinkler versus drip irrigation for increased water use efficiency and profitability when water is scarce[118].

Background

Lockyer Valley, Southern Queensland. Max Durham farms approximately 300ha of alluvial black-earth soils both by the banks of Lockyer Creek, and on surrounding leased land. He has been using overheads to irrigate different vegetable crops.

By 2003/04, after consecutive years of drought and below-average rainfall in the Lockyer Valley, water levels in the aquifer supplying irrigation to the farm had dropped to the lowest levels ever across much of the farm. Faced with this potential water shortage, Max stopped using turbine pumps down bores, replaced them with submersibles, and built three turkey-nest dams for storing water. With the existing overhead sprinklers, the available water was not sufficient to produce vegetables to meet his long-term market commitments.

Max's initial response was to consider markedly reducing the area under vegetable cropping. This would have meant losing market access (retail chains, processing factories), built up over 15 years, and not easily recovered once lost.

In order to retain his market access, he decided to change from overhead sprinkler irrigation (solid-set or hand-shift) to drip irrigation: this would help in reducing the per hectare use of water and thus increase the area that could be cropped from the limited water supply. As a result of his switch to drip irrigation, Max was effectively able to increase the cropping area threefold, compared with overhead only.

Overhead sprinklers are still used for the first irrigation after transplanting to establish the transplanted lettuce and broccoli seedlings. Overhead sprinklers can also be used immediately prior to harvest for their cooling effect, if the weather turns unseasonably warm. The change in systems has helped Max to increase the area under lettuce and broccoli substantially.

The objectives of this economic study were to work out the additional costs and benefits from switching over to drip irrigation and to measure the returns on the farmer's investment in adopting drip irrigation.

Economic analysis

It is assumed that, in a normal season, when more water is available, the farmer will be able to grow the same area of lettuce and broccoli. The only savings from his change to a drip

[118] Hickey, Hoogers, Singh, Christen, Henderson, Ashcroft, Top, O'Donnell, Sylvia & Hoffmann (2006) Maximising returns from water in the Australian vegetable industry: National report

system are assumed to be water and fertilisers. Information on area sown, input use, crop yield and output prices of broccoli and lettuce grown using overhead and overhead irrigation are given in Table 25.

Table 25. Area, input use, crop yields and prices of different vegetables grown using different irrigation technologies

	If overhead only:		Drip with start (and finish) overhead:	
	Lettuce	Broccoli	Lettuce	Broccoli
Area sown	25 ha	9 ha	82 ha	28 ha
Yield	3250 cartons/ha	1050 cartons/ha	3250 cartons/ha	1050 cartons/ha
Fertiliser use	100%	100%	50%	50%
Irrigation required (assumes some rain)	2.5 ML/ha	2.5 ML/ha	Winter 0.875 ML/ha Aut/Spr. 1.25 ML/ha	Winter 0.875 ML/ha Aut/Spr. 1.25 ML/ha
Price ($/carton)	$12.00	$16.00	$12.00	$16.00

When growing vegetables with drip irrigation, the cropping season is longer than with overheads. This helped the grower to pump out more water and significantly increased the area under lettuce and broccoli from 34 hectares under overheads to 110 hectares when using drip irrigation. It was found that the crop yield, output prices and labour requirements were the same but water and fertiliser use declined significantly under drip compared with overhead irrigation (Table 25).

Since switching over to drip irrigation has been incremental; both drip and overhead systems use the same mains and sub-main systems throughout the farm. Where necessary, the hydrants and main pump are throttled back so as not to over-pressurise the drip tape.

Drip tape can only be used for one season and therefore, in the gross margins for drip-irrigated broccoli and lettuce, the cost of 10,000 metres of tape per hectare for lettuce on beds and 6,700 m tape/ha for broccoli on 1.5 m beds has been considered. Details of the capital costs, operating costs and repair and maintenance costs involved in switching to drip irrigation from the existing overheads are given in Table 26.

To switch over to drip irrigation, the grower invested $60,000 in altering machinery to cope with installation, new bed sizes, drip removal, and so on. The expected life of the machinery is 20 years. It would require an additional cost of $20,000 for major repairs and replacement of some components after 10 years.

The layout requires three new sand filters (one for each turkey nest), at about $11,000 each. Filters last 20 years and cost $500 every 5 years to replace sand and maintain. The setup also requires a set of disc filters every 10 hectares, each costing $400, with a life of 10 years. The study has budgeted for 5 sets only, as not all of the crop is in the ground at once, and therefore the sets can be used more than once during the season. The system required 75mm layflat, using 35 metres per irrigated hectare, with an anticipated life of 3 years. The farmer used a total of 1500 metres of layflat for the whole area.

Table 26. Capital costs, operating costs, maintenance and replacement costs involved in switching to drip irrigation for growing lettuce and broccoli

Measure	Expenditure
Number of filters required	3
Repair and maintenance ($)	$500.00
Cost of disc filters ($/filter)	$400.00
Number of filters	5
Life of filter (years)	10
Expected life of drip (years)	20
Layflat pipe (metre)	1500
Anticipated life layflat (years)	3
Irrigation scheduling (tensiometer)	$1000.00

Benefit-cost analysis

The results show that this conversion has been a sound investment. With the present value of benefits at $15.3 million, and the present value of costs at $63 400, the net present value of benefits from drip irrigation is $14.62 million. The benefit–cost ratio is estimated at 24.04 (Table 27). The analysis further reveals that the farmer is able to recover the costs of switching to drip irrigation in the first year.

Table 27 Results of the benefit–cost analysis of adoption of drip irrigation on the case study farm

Measure	Value
Present value of costs	$63 400
NPV benefits	$14 620 000

7.1.8 Postharvest cooling and temperature management

The main greenhouse gas emissions from the Australian vegetable industry are from electricity use to run irrigation pumps and cool rooms, and together they account for 66% of emissions.

The vegetable industry also needs to get produce to market, retailer or to the processor at the right temperature and in good condition. The grape industry is similar to the vegetable industry in that it also has a high-energy requirement for cooling grapes to ensure they are delivered to the winery cool, and in good condition.

There has been a great deal of emphasis on cooling vegetables as quickly as possible and getting them to market in the best possible condition, however, paradoxically, this may mean that produce is now being cooled in excess of requirement just to be sure it meets delivery specifications.

It may be that cooling produce within 4 hours makes only a small difference to shelf life or quality than it would if it were cooled, say, within 1 hour. While there is good evidence that rapid cooling of crops such as lettuce using high-energy methods such as vacuum cooling does prolong the shelf life, it may be the case that cooling within 4 hours is good enough to meet market requirements. This may also hold true for other similar leafy crops such as spinach, and even for other rapidly respiring crops such as broccoli.

The focus on postharvest cool-chain research has been to maximizing shelf life and quality with less focus on the energy and capital investment required to achieve these outcomes.

The opportunity in this area is to approach the postharvest temperature management question from a different perspective. If we ask the question:

How can we cool our produce in such a way that minimizes the energy requirement for a given level of quality and shelf life?

Will we open up a whole range of possible new handling practices?

Some potential research questions might include:

- What temperature do we need to achieve the shelf life and quality required for a given end-use? Do we always simply aim for maximum shelf life?

- Are there more efficient ways of managing field heat in produce? For example, should we be harvesting at night before much of the field heat accumulates in produce rather than allowing crops to heat up before harvest and then trying to remove that heat after harvest.

- How ***quickly*** do we need to get produce to the target temperature to provide ***adequate*** shelf life and quality?

- What is the ***target temperature*** for acceptable shelf life and quality of a crop for a given end-use?

Two good examples of how this approach has been used are with seedless watermelons and wine grapes.

Seedless watermelons: The ideal storage temperate is 7-10^{o}C, which gives a shelf life of 21 days and 14 days at 15^{o}C (UC Davis). Research on seedless watermelons in Australia discovered that as long as fruit was kept below 25^{o}C it had an acceptable shelf life of about 14 days or more and that refrigerated transport was not required to deliver an acceptable product to the consumer[119].

Wine grapes: are now almost universally harvested at night when they are cool and transported to the winery early before the heat of the day. This has effected a major improvement in grape quality delivered to the winery, and a significant saving in energy by not having to remove field heat from grapes before crushing[120].

[119] HAL project VX04001
[120] GWRDC (2003). A guide to energy efficiency innovation in Australian wineries.

7.1.9 Protected Cropping

Protected cropping accounts for a significant slice of the vegetable and flower industries in Australia, with a current annual GVP of about $1.3 billion[121] or about 16% of the total GVP for horticulture of $8.4 billion (ABS). There are about 1,300 ha of greenhouses in Australia with an average infrastructure value of $75/m^2 (Table 28).

The industry is currently expanding at a rate of a rate of 25 ha of new structures per year with the cost of building new structures valued at $200/m^2 or at ($50 million) per year.

Table 28. Area of greenhouse vegetable production in Australia

State	Greenhouse area (m2)	No. of growers
Qld	30	80
NSW	500	680
Vic	200	200
SA	580	650
WA	21	30
Tas	10	25
Totals	**1341**	**1665**

Source: Protected Cropping Australia[122]

Types of structures

There are three broad classes of protected cropping generally referred to by industry as low tech, medium tech and high tech.

- **Low structures** are usually plastic covered igloos with minimal ventilation and heating (Figure 41).
- **Medium tech** structures are more sophisticated, with computerised ventilation systems, heating and growing systems. The structures themselves are large multi span buildings with automated ventilation and shading systems but the coverings are usually a form of plastic (Figure 42, Figure 43).
- **High tech** structures are the most sophisticated growing systems available with advanced computer-controlled heating and cooling systems, CO_2 enrichment, large conglomerate structures covering large areas, up to 25ha in Australia. The covering material is usually glass (Figure 44).

121 Graeme Smith Consulting
122 Protected Cropping Australia: www.protectedcroppingaustralia.com

Figure 41. Low-tech igloo-style greenhouse.

Figure 42. Medium-tech greenhouse exterior.

Figure 43. Medium-tech greenhouse interior.

Figure 44. High-tech glasshouse in Canada with hi-tech greenhouse facilities that generate renewable electricity, and harvest rain and runoff water. (Houweling Nurseries)

Productivity

The yield potential from protected cropping is much higher than is possible to achieve from normal outdoor production, with potential improvements ranging from 250 to 800% (Table 29) shows an average yield comparison between protected cropping and field production for a range of vegetables.

Table 29. Average yields available from protected cropping compared to open field production[123]

Crop	Tomatoes	Capsicum	Cucumber	Lettuce
Greenhouse (kg/m^2)	76	30	100	80
Field (kg/m^2)	18	12	20	10
Increase (%)	422	250	500	800

The yield differences are highly dependant on the level of sophistication of the greenhouse. Table 30 shows the relative yields for tomatoes, capsicums, cucumbers and lettuce for the three types of greenhouse production systems.

Table 30 Relative yields from low tech, medium tech and high tech protected cropping [123]

Kg/m^2/year	Low tech	Medium Tech	High Tech
Tomatoes	25 - 35	35 - 55	65 – 105
Capsicums	15 -20	20 - 25	30 - 33
Cucumbers	60	88	120
Lettuce	30	60	90

7.1.9.1 Protected cropping as a climate change mitigation option

The protected-cropping industry is likely to be least affected by the physical impacts of climate change and increased climate variability and as such it may be a very useful adaptation strategy to allow production to continue, especially in areas close to retail markets. Temperature can be regulated to a large extent, and heating of greenhouses located in cool regions is becoming more energy- and emissions-efficient all the time.

Protected cropping and associated hydroponic irrigations systems are very efficient users of water. Fruit and vegetable growing generally uses about 38L of water per dollar of value produced, whereas hydroponically-produced vegetable crops use only 0.6L of water to produce the same value (Table 31).

[123] source: Graeme Smith pers. Comm.

Table 31. Water-use efficiency from protected cropping with hydroponics [125]

Agricultural sector	Water use efficiency (L water / $ value)
Rice	475
Cotton	160
Dairy	147
Sugar	124
Beef cattle	81
Fruit and vegetables	38
Grains	25
Protected cropping with hydroponics	0.6

The main concern with greenhouse production is the energy that is consumed in construction, maintenance and production of the crops. Structures tend to have:

- High energy-use for heating and cooling.
- High energy-inputs into the construction of greenhouses and in the manufacture of materials.

This could be a disadvantage for greenhouse production in an energy-conscious world.

7.1.9.2 Energy use and GHG emissions of protected cropping v's field production

The energy use of a greenhouse can be explained in terms of electricity use or thermal.

The typically electricity use for a greenhouse is about 10kWh/m^2/year and this includes all aspects of the enterprise (e.g., production, administration, grading & packing, coolroom, therefore 100kMh/ha/year for the operation[124].

From a thermal perspective, each greenhouse load is calculated on local climate and crop type but typical use (modern system) would be in the order of 35m^3/m^2/year of natural gas. This equates to 350,000m^3/ha/year or 13,580,000MJ/ha/year (calculated at maintaining an average 24hr greenhouse temperature of 20^{0}C)[124].

There is a QDAFF and NSW DPI project currently underway: *Energy Efficiency in Australia Glasshouse Horticulture* and this project is expected to deliver useful data energy on protected cropping. This project has produced two manuals so far on how to undertake a greenhouse energy assessment[125].

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[124] Graeme Smith pers comm.
[125] Greenhouse energy assessment: Design and management principles for improved efficiency. Hunt, Dembowski and Badgery-Parker (2012). Qld DAFF.

7.1.9.3 Use of screen houses or shade cloth to reduce water use and heat damage in field-grown crops

A very interesting potential use of low-cost protected cropping as an adaption to the impacts of climate change is the use of screen houses or shade cloth to protect field-grown crops from excessive heat and sunburn.

Preliminary trials by growers in Griffith, supported by the NSW Department of Primary Industries (DPI), indicate that a new Israeli technique using screen houses could see water used for growing vegetables cut by more than a third.

An Israeli research trial, reported last year in the journal *Irrigation Science*, found 38% less water was required for screen-house crops compared with crops grown in open fields. The shade cloth reduces sunlight penetration and reduces wind speed around the crops. NSW DPI says *the Australian trial is supporting overseas findings that sunlight intensity, wind speed and evaporative losses from the plant and soil surface were all lower and provided a more favourable environment for plant growth*.

The technique has been used successfully for melons and mini capsicums, and is estimated to reduce radiation levels by 40%. This means crop water use is reduced, which is a significant benefit in terms of reducing water use but makes water management crucial, as excess water can lead to root diseases such as *Pythium* and *Phytophthora*. The Griffith growers believe the screen house is economically viable, but the cost-benefit of the system for other growers still needs to be assessed[126].

7.1.9.4 Opportunities for energy efficiencies in relation to protected cropping: Combined heat and power systems (CHP)

Combined heat and power or CHP, also called cogeneration or distributed generation, is the simultaneous production of two types of energy – heat and electricity – from one fuel source, often natural gas. The ability to create two forms of energy from a single source offers improved efficiency, cost savings and reduced energy consumption. A natural gas-fired engine powers a generator to produce electricity, and the by-product of the working engine is heat. The heat is captured and can be used to heat the greenhouse. The CHP process is very similar to an automobile, where the engine provides the power to rotate the wheels and the by-product heat is used to keep the passengers warm in the cabin during the winter months.

Combined heat and power systems use fuel very efficiently. A CHP system provides electricity and heat at a combined efficiency approaching 90%. This is a significant

[126] Sun shield reduces water needed to grow vegetables: southern NSW trial. NSW DPI Science and Research newsletter, 2007.

improvement over the combination of the 35%-efficient electric utility and a conventional heating boiler with a 65% seasonal efficiency.

Because of the high efficiency of these systems, CHP systems can reduce the demand on the utility grid, increase the energy efficiency of an operation, reduce air pollution, lower greenhouse gas emissions and protect the property against power outages and lower the utility costs of building operations.

Figure 45. CHP system in California: A Jenbacher J624 two-staged turbocharged natural gas engine. Credit: © GE

America's first Combined Heat and Power (CHP) project that captures carbon dioxide to help fertilise tomatoes has been unveiled. Houweling's Tomatoes in California has installed two General Electric Company (GE) 4.36-megawatt (MW) Jenbacher J624 two-staged turbocharged natural gas engines and a carbon dioxide fertilisation system to provide heat, power and carbon dioxide to the 50-hectare tomato greenhouse in Camarillo. One Jenbacher J624 two-stage turbocharged gas engine can provide electrical power for about 4,400 average homes, saving about 10,700 tons of CO_2 per year compared to coal-fired power generation. CHP systems can also be powered by biogas systems, which use farm or other organic waste as the energy source. These systems can be very efficient for larger vegetable farms which produce more that 10 tonnes of waste per day. Refer to the VG12049 report for more details.

7.1.9.5 Opportunities for energy efficiencies in relation to protected cropping: Urban farming systems – Aquaponics.

Aquaponics, which combines aquaculture with hydroponics to produce fish and vegetables in the one structure is an inherently energy-efficient system and could have significant potential to produce vegetables close to urban centres. The design of these systems recycles waste produced by the vegetable crops and uses the fish effluent as a nutrient source for the plants. Energy collected within the glasshouse can be used to heat water in fish tanks and also store it for later use in the greenhouse. There is a 0.8 ha commercial pilot system in operation at Camden in NSW operated by Urban Ecological Systems in a joint venture arrangement with the University of Sydney[127].

7.1.9.6 Case study: Field versus glasshouse tomato production

The following case study was prepared by Graeme Smith and it compares field tomato production with production in a modern glasshouse situated only a few kilometres away.

The following production figures of field and glasshouse are from the 2006 growing season and are converted to a per-hectare basis so that direct comparisons can be made.

Table 32 Comparative data from open field and glasshouse tomato production in Australia[128]

	Field	Glasshouse	Change (%)
Study unit size (ha)	1	1	0
Plant density (plants/ha)	11,000	22,000	100%
Yield (t/ha)	69.2	585	845%
1st Grade fruit (%)	80	95	12
Yield of 1st grade fruit (t/ha)	58.8	555.7	944%
Yield 1st grade fruit per plant (kg/plant)	5.3	25.3	472%
Water Use (ML/ha)	8	14.5	182%
Water use efficiency (t/ML)	8.7	40.2	465%
Market Returns (gross)$	$82,385 (at $1.40/kg)	1,667,250 (at $3/kg)	2,024%
Cropping period (months)	7	11.5	164%

Modern glasshouses using closed and controlled production systems are capable of delivering superior results to open field production in terms of quantity, quality, water use and market returns.

127 Hogan Gleeson info@ecocityfarm.com.au
128 Graeme Smith pers comm.

When reviewing the production figures, it appears on the surface that greenhouse production uses more water than field production. However, greenhouse production occurs for 11.5 months of the year compared to 7 months for field production. The greenhouse production figures also include all water used, not just that put on crops (i.e. fogging, roof sprinklers, hand washing and other staff facilities). The important point is that the water-use efficiency of glasshouse tomato production is nearly 5 times higher than for field production.

Supermarket chains have signalled to industry their intention to increase greenhouse tomato sales from the current estimated 17% (of fresh table market) to 50% over the next 5 – 8 years, a tripling of one sector of the greenhouse industry for one crop.

Industry expectations are that the same growth pattern shall occur for other greenhouse crops such as capsicum, eggplant, cucumber, lettuce, Asian vegetables and strawberries.

In summary, some of the advantages of protected cropping over open field production are:

- Closed systems can deliver near zero wastewater all year round.
- Smaller water and energy footprints, therefore less impact on the natural environment.
- Marginal land can be used.
- Controlled environment allows better use of IPM and beneficial insects with much reduced sprays.
- Higher Brix (sugar) levels delivers sweeter, more flavoursome fruit and longer shelf life.
- Year-round supply of consistent quality and quantity to meet consumer needs.
- Environmentally sound and responsible growing system.
- No weeds, no weeding, no herbicides.
- Higher production per hectare (1ha glasshouse produces the same as 9.4ha field).
- Higher returns for farmers' efforts.

Graeme Smith (CPAg) is the principal of Graeme Smith Consulting and President of the Australian Hydroponic & Greenhouse Association.

7.1.10 Better use of models for managing crops – based on APSIM model

There is the potential to make more of the mechanistic APSIM models, which are being used by other industries to model predicted changes to crops in response to climate change.

Examples of models based on APSIM are:

- GrassGrow – pasture model
- AussieGrass – pasture model
- Dairy Mod – dairy/pasture model
- MLA – future climate modelling for the livestock industry

The vegetable industry could undertake two main activities in this area:

1. Model future scenarios, looking at sowing times, and the effectiveness on yield and profitabilty of various adaptation strategies to climate change.

2. Support elevated CO_2 work on new varieties to see how they will respond to higher CO_2 levels, investigate pest and disease interactions and play a role in the breeding of new varieties. Modelling would play a crucial role in these activities.

7.2 Mitigation options

Vegetable industry emissions are described in detail in section 4.2. The main indirect emissions are from electricity for refrigeration and pumping water and the main direct emissions are nitrous oxide emissions from soils.

In horticulture, high nitrogen rates are combined with moist, warm soils and this combination can result in very high nitrous oxide (N_2O) emissions rates, far in excess of the average emissions rates for vegetable production. There has not been sufficient research into N_2O emission rates from Australian vegetable soils and there is clearly a need to rectify this deficiency, something that has been recognised by the DAFF Filling The Research Gap program[129].

There are three main ways that greenhouse gas emissions can be reduced from vegetable farming operations:

1. Reduce electricity use for pumping and refrigeration, or generate power on farms from renewable energy sources.
2. Reduce N_2O emissions from soils.
3. Sequester carbon in soils.

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[129] http://www.daff.gov.au/climatechange/carbonfarmingfutures/ftrg

7.2.1 *Improve on-farm energy use efficiency*

Indirect CO_2 emissions could be by reduced by reducing farm electricity consumption, which is used mainly for pumping irrigation water and running cool rooms (refrigeration)[130]. This can be achieved by either improving the efficiency of pumps and refrigeration, or by on-farm power generation using renewable energy sources. These options have been reviewed under the related project VG12049[131].

7.2.2 *Nitrous oxide emissions*

There are many options available for reducing N_2O emissions from soils:

- Reducing N_2O loss through chemical routes, to increase the rate of denitrification – nitrification inhibitors.
- Cost-effective, slow-release nitrogen fertiliser products, which reduce gaseous nitrogen emissions in synergy with increased productivity and profitability.
- Managing the relationship between soil carbon and nitrogen (e.g. potential increases in N_2O emissions as soil carbon is increased).
- Improved nitrogen management.
- Improved irrigation management, especially sub-surface drip irrigation.

7.2.3 *Sequestering carbon in soils*

Sequestering carbon in soils for the long term (100 years) can be an effective way of taking CO_2 out of the atmosphere. However, there is a need for improved understanding of management practice on soil-carbon change before these options can be properly assessed. Some methods that have potential for achieving this in the vegetable industry include:

- Biochar
- No-till and controlled traffic
- Cover crops and incorporation of organic matter
- Manures

There is a detailed review of greenhouse gas emissions from sustainable vegetable cropping systems included in this report as Appendix 11.1

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130 Rab, M. A., P. D. Fisher, et al. (2008). Vegetable Industry Carbon Footprint Scoping Study – Discussion Papers & Workshop. 4. Preliminary Estimation of the Carbon Footprint of the Australian Vegetable Industry.

131 Understanding and managing impacts of climate change in relation to government policy, regulation and energy efficiency HAL Project VG12049.

7.2.4 Carbon farming initiative (CFI) methodologies

The Carbon Farming Initiative (CFI) is a voluntary carbon offsets scheme. This Australian Government initiative allows farmers and land managers to earn carbon credits by reducing greenhouse gas emissions (such as nitrous oxide and methane) and storing carbon in vegetation and soils through changes to agricultural and land management practices (also known as carbon farming).

These credits, known as Australian Carbon Credit Units (ACCUs), can be sold to individuals and businesses that want or need to offset the greenhouse gas emissions of their business operations. This can create additional income for Australian farmers and land managers who choose to take part in the initiative.

To participate in the CFI, people undertaking projects to reduce their greenhouse gas emissions or store carbon in the landscape will need to use an approved methodology for their activity. These methodologies contain the detailed rules for implementing and monitoring specific carbon farming activities and generating carbon credits under the scheme. New methodologies and opportunities to participate are continually evolving.

The CFI and its relevance to the vegetable industry has been reviewed as part of project VG12049.

8 Review of current research

8.1 Current Primary Industries Investment in Climate Change RD&E

Across all primary industries there were 589 climate change research projects active in 2011-12, with a value of $549 million over the life of the projects ([132]). This represents a per-annum investment of $157 million.

Investors in these current RD&E activities are one-third Industry RDCs, one-third State Agencies and one-third Federal Government (DAFF, Australian Research Council, CSIRO). This balance will change with the substantial investment by the Federal Government through the Filling the Research Gap Program run by DAFF and the closing of many climate change programs at the State level.

8.2 Horticultural Climate Change RD&E Investment

In the broader horticulture sector, including grape and wine, there were 44 RD&E projects with a combined value of $21.5 million, at $7.6 million per year (see Appendix I for projects).

The horticultural sector, while only representing 4% of the total investments, has taken a comprehensive approach (Figure 34).

More than half of the investment is in managing climate variability and adapting to changes in water availability and temperatures. This RD&E has immediate application.

Specific research to reduce greenhouse gas emissions, sequester carbon and improve and work with climate change predictions accounts for 44% of the investment.

Research is also underway that examines how horticulture can manage energy use, adapt to new policies and understand the drivers for change.

[132] CCRSPI Audit Report. Collation and analysis of RD&E activities. August 2012.

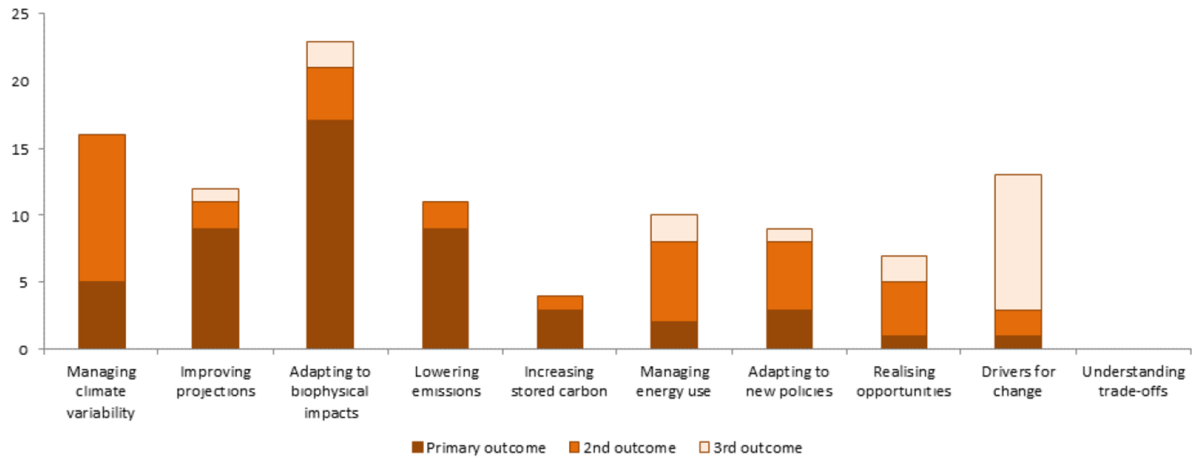


Figure 46. Areas of investment in climate change RD&E for horticulture.

8.3 Investment by the vegetable sector

The vegetable sector has $8.3 million invested in climate change research. Furthermore, the vegetable sector benefits from the $6.5 million invested in the cross-horticulture understanding of climate change.

The vegetable-sector RD&E projects are predominantly delivered by State departments, with limited involvement by universities and private providers.

Given the small overall proportion of RD&E investment in climate variability and change by horticulture, there are real opportunities to partner with other primary industry sectors. This would increase the efficiency of the RD&E investment and increase the influence of the horticultural sector in dealing with other organisations such as Bureau of Meteorology and CSIRO for such outputs as forecasts of extreme events, e.g. frost, and tailoring climate projects to the horticultural sector.

8.4 What are other industries doing?

The livestock industries (dairy, beef & sheep) investments in RD&E are focused on mitigation through lowering emissions (Figure 47). Nearly all of this investment is directed towards reducing methane emissions from the rumen.

The livestock sector also made a reasonable investment in understanding and managing climate variability and change. There is also a strong emphasis on understanding the impacts of policy.

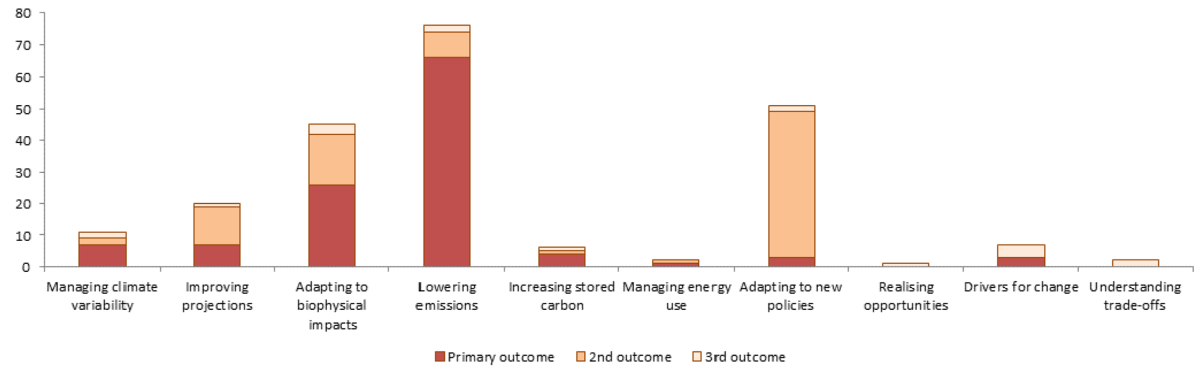


Figure 47. Livestock sectors investment in different areas of climate change RD&E. (Values are $millions over approximately 3 years.)

The cropping industries (grains, cotton, sugar, rice) investments in RD&E are focused on adapting to climate variability (Figure 48). These industries, in particular the rain-fed cropping systems, are at the cutting edge of managing climate variation. As such they have made substantial investments in both understanding and managing climate variability and change and how their industry can adapt.

A key investment has been in the Managing Climate Variability Program that works to improve climate forecasting, and tailoring this to agricultural requirements.

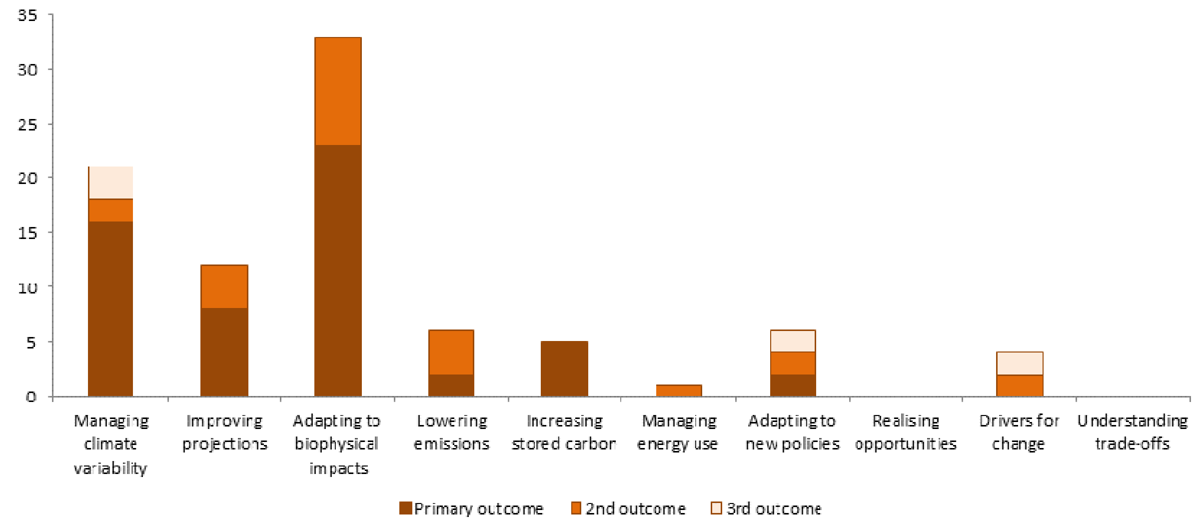


Figure 48. Cropping industries investment in different areas of climate change RD&E. (Values are $millions over approximately 3 years.)

8.5 Current horticulture-related climate change projects: March 2013

8.5.1 ***Horticulture Australia***

Vegetable sector

- Quantifying the effects of no till-vegetable farming and organic mulch on greenhouse gas emissions and soil carbon.
- Impact of subsurface drip irrigation and soil health on greenhouse gas emissions and productivity of processing tomatoes.
- The impacts of the proposed carbon price mechanism on Australian horticulture.
- Opportunities for Australian horticulture in the Carbon Farming Initiative.
- Across-industry climate research, development and extension (RD&E) activities.
- Economic and carbon emissions model for controlled-traffic farming in vegetables.
- Novel, sustainable and profitable horticultural management systems: soil amendments and carbon sequestration.
- Understanding the carbon and pollution mitigation potential of Australia's urban forest.
- Increasing energy efficiency and assessing an alternate energy option for Australian Protected Cropping.

Other horticultural projects

- Apple and pear climate change program.
- Design and demonstration of precision agriculture irrigation applied to different vegetable crops.
- Effectively utilising water allocations for managing turfgrass in open spaces.
- Optimising water use of Australian almond production through deficit irrigation strategies.
- Identification and evaluation of water conservation products and technologies for the Australian urban outdoor market.
- Greening City - mitigate heat stress with urban vegetation.
- Citrus drought survival and recovery trial.
- Wild about macadamias - conserving a national icon.
- Cherry cultivar selection: chill hours and climate change.
- Warm season grass evaluations for turf in cold climates.
- Adaptation of warm-season turf grasses for tropical Australia.

8.5.2 Department of Primary Industries, Parks, Water and Environment, Tasmania

Vegetable sector

- Precision agriculture irrigation applied to different vegetable crops.
- Development and demonstration of controlled-traffic farming techniques for production of potatoes and other vegetables.
- On-farm demonstrations of controlled-traffic farming for vegetables.

Other horticultural projects

- Developing climate change adaptation research in Tasmania.
- Quantifying relative contribution of physiological traits.
- Soil organic carbon balances in Tasmanian agriculture systems.
- Wealth from Water Program.

8.5.3 Department of Primary Industries, Victoria

Vegetable sector

Nil

Other horticultural projects

- Modelling climate change impacts on perennial horticulture (08638).
- Regional climate change impact on horticulture.
- Water and climate change in horticulture industries.
- Delivering a route to market for horticulture climate change research.
- Managing disruption to water supply in perennial horticulture in a changing climate.

8.5.4 Department of Primary Industries, NSW

Vegetable sector

Nil

Other horticultural projects

- Flesh browning for Cripps pink apples.

8.5.5 Department of Agriculture, Fisheries and Forestry, Queensland

Vegetable sector

- Energy efficiency in Australian glasshouse horticulture.

Other horticultural projects

- Climate change and climate policy implications for the Australian avocado industry.
- Critical temperature thresholds and climate change in horticulture.

8.5.6 Department of Agriculture, Fisheries and Forestry, National

Vegetable sector

- Horticulture: taking action to capture carbon and reduce nitrous oxide emissions.
- Carbon and sustainability – a demonstration of how they relate and how they can be managed within the Australian vegetable industry.

Other horticultural projects

Nil

8.6 Horticulture: review of past climate change projects

There have been extensive reviews carried out recently that describe the likely impacts of climate change and increased variability on horticulture in general and vegetables in particular. These studies have been collected as part of this review and posted on the *Vegetable Climate* website (www.vegetableclimate.com).

The most relevant reviews and information sources on climate change relevant to horticulture in Australia are:

- *Climate Change and the Australian Horticulture Industry (CCRSPI 2012).*
- *Scoping study into climate change and climate variability (Deuter 2006).*
- *Horticulture climate change action plan (HAL 2009).*
- *Horticulture and climate change website http://www.daff.qld.gov.au/26_14576.htm (Deuter 2012).*
- *Australian horticulture's response to climate change and climate variability (Deuter 2009).*
- *Garnaut Climate Change Review: Defining the impacts of climate change on horticulture in Australia (Deuter 2008).*
- *The impacts of the proposed carbon price mechanism on Australian horticulture (Putland 2012).*
- *Opportunities for Australian horticulture in the Carbon Farming Initiative (Putland, 2012).*

8.7 Vegetables: review of past climate change projects

In relation to vegetable production and the industry specifically, there have been a number of important reviews and studies that have been consulted and referenced as footnotes in this report. This review does not attempt to repeat the information presented in these publications however summaries are provided on the *Vegetable Climate* website (www.vegetableclimate.com).

The important Australian vegetable-specific publications reviewed included:

- *Potential impact of climate change on plant diseases of economic significance to Australia. Australasian Plant Pathology (1998) 27: 15-35*
- *Opportunities and challenges faced with emerging technologies in the Australian vegetable industry (Estrada-Flores 2010)*
- *EnviroVeg Program: Case studies 2010 - 2011*
- *Vegetable Industry Carbon Footprint Scoping Study - Discussion Papers and Workshop series (1-6):*

    - *What is a Carbon Footprint? An overview of definitions and methodologies (East 2008)*
    - *How will carbon footprinting address the issues of reduction, mitigation, emissions trading and marketing? (Deurer, Clothier et al. 2008)*
    - *What carbon footprinting tools are currently available? (Lisson 2008)*
    - *Preliminary Estimation of the Carbon Footprint of the Australian Vegetable Industry (Rab, Fisher et al. 2008)*
    - *Who will use the vegetable carbon tool? (Deuter 2008)*
    - *Options for mitigating greenhouse gas emissions for the Australian vegetable industry (O'Halloran, Fisher et al. 2008)*
- *An assessment of greenhouse gas emissions from the Australian vegetables industry. Journal of Environmental Science and Health Part B (2010) 45, 578–588*
- *Critical temperature thresholds Case study: Lettuce (Deuter, White et al. 2011)*
- *Critical temperature thresholds Case study: Tomato (Deuter, White et al. 2011)*
- *Understanding Victoria's Fruit and Vegetable Freight Movements. (Marquez et al, 2010)*

Other relevant vegetable specific publications include:

- *Climate change: a response surface study of the effects of CO2 and temperature on the growth of beetroot, carrots and onions. Journal of Agricultural Science, Cambridge (1998), 131, 125-133.*
- *Investigating trends in vegetable crop response to increasing temperature associated with climate change. Scientia Horticulturae 66 (1996) 255-263.*
- *Climate changes and potential impacts on postharvest quality of fruit and vegetable crops: A review. Food Research International 43 (2010) 1824–1832.*
- *Climate Change and Its Impact on the Productivity and Quality of Vegetable Crops. Journal of Applied Sciences Research, 8(8): 4359-4383, 2012.*

9 Climate change management tools

There is a wide range of tools available for helping growers and industry-support professionals to manage and understand the impacts of climate change in agriculture. These tools can be grouped into five main categories:

1. Managing climate
2. Forecasting
3. Understanding the climate
4. Carbon footprinting
5. Financial management

9.1 Tools for managing climate

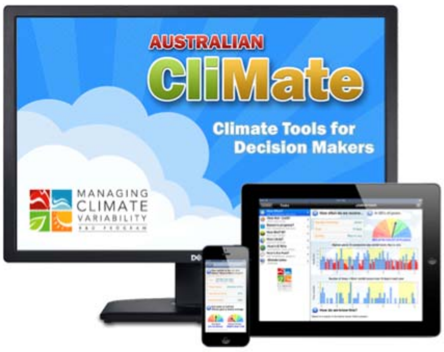
Climate tools are not always used by growers in an ongoing way[133], but there have been two notable exceptions. The ***Australian CliMate*** tool and ***Yield Prophet***® have been very popular with excellent uptake by growers.

The Climate Kelpie website[134] administered by the Managing Climate Variability (MCV) program has a list of the useful and validated tools currently available for managing climate. The full suite of tools available for assisting in managing climate across all agricultural industries is listed in Table 34. The tools the Climate Kelpie website considers relevant for horticulture are described in more detail in the following section and are highlighted in Table 34.

1. Australian CliMate
2. CropMate
3. Irrigation Optimiser
4. Rainman StreamFlow
5. SILO

133 Dr Beverly Henry, Program coordinator. Managing Climate Variability Program.
134 http://www.climatekelpie.com.au/

9.1.1 Australian CliMate



CliMate is a suite of climate analysis tools delivered on the Web, iPhone, iPad and iPod touch devices. CliMate allows you to interrogate climate records to ask a number of questions relating to rainfall, temperature, radiation, as well as derived variables such as heat sums, soil water and soil nitrate. CliMate also provides information based on El Nino Southern Oscillation patterns. It is designed for decision makers who use past weather statistics, forecasts and knowledge of system status (e.g. soil water, heat sum) to better manage their business.

CliMate has a number of analyses structured around the following questions:

- How often? What is the chance of a sowing event based on amount of rainfall over 5 days? How often is a heat sum achieved in a set period of time? What is the probability of temperature being below a critical level for germination or flowering?
- How hot-cold? When determining an ideal sowing date, when are heat and cold stresses lowest for the optimum flowing time?
- Season's progress? When adjusting inputs during a crop or pasture season, how does the current season compare with previous conditions in terms of rainfall, temperature, heat sum or radiation?
- How wet? N? How much water and nitrate have I stored over the fallow? This may help me adjust inputs to better match yield expectations.
- How likely? Based on current ENSO conditions, what is the probability that rainfall or temperature is greater than or less than key thresholds (e.g. terciles, median) and how reliable have these forecasts been in the past?
- How's El Nino? What is the current ENSO status based on key atmospheric and oceanic indicators? What is the Australian Bureau of Meteorology's interpretation of this?
- How dry? Coming Soon! Based on recent rainfall records, are we likely to be facing a drought in the near future or are we in a drought now? And how do current dry conditions compare with previous droughts?
- How's the Past? Presents views of monthly and annual rainfall and temperature summaries to allow you to explore relationships and patterns.

How to get it

Go to the CliMate website http://www.australianclimate.net.au/ or download from the Apple App Store.

9.1.2 CropMate

CropMate is a web-based application that helps growers analyse climate and weather information for their location so that they can make informed planning and management decisions at different points during the crop cycle. The tool is designed to assist farmers, agronomists, consultants and people working in landscape management in grain-producing regions of eastern Australia.

It can be used to calculate seeding rates, compare prices of fertilisers, or work out which varieties will be most profitable to plant, given the available climate and soil information. The variety information is based around grains but the climate aspects are relevant to the vegetable industry.

CropMate™ is divided into 5 modules, which match the 5 stages of the crop cycle and these modules are shown in Table 33. CropMate™ is available on the web. The VarietyChooser module is available as a free VarietyChooser app (for iPad/iPhone).

Table 33. Examples of the modules available in CropMate™

Stage in the crop cycle	Module	Helps you to
1. Preseason planning	Frost and heat risk	Assess frost and heat risk
	Estimating soil water	Estimate soil water
	Estimating soil nitrogen	Estimate soil nitrogen
	CropChooser	Choose the most profitable crop to grow
2. Sowing	SowMan	Determine the appropriate sowing date for a wheat or barley crop at your location
	Nitrogen budgeting	Budget nitrogen to use
	Phosphorus budget	Budget phosphorus to use
	VarietyChooser	Compare the disease ratings and yield performance of varieties
	Sowing rate calculator	Calculate sowing rate
	Fertiliser calculator	Calculate fertiliser application rate
3. Spraying		Determine spray time / application rate
4. Growing season	Salvaging crops for fodder, grain and grazing	Determine if/when you should salvage crops for fodder
	Nitrogen topdressing	Calculate the amount of nitrogen to use in top-dressing
5. Harvest	Post-harvest review	Review your crop post-harvest

How to get it

CropMate is available at http://cropmate.agriculture.nsw.gov.au/

9.1.3 Irrigation Optimiser

Irrigation Optimiser helps growers to decide what irrigated crops to plant based on water availability. The tool may have applicability for vegetable producers, but all the development work and testing has been carried out with rice or grain producers.

Irrigation Optimiser is a web-based tool that identifies the optimal allocation of water and land for a grower's irrigated farming system. It calculates expected yield, costs, amount of water, optimal area, gross margin and profit for each crop.

The aim of the irrigation optimiser is to help growers be better prepared to:

- Cope with the impact of increased climate variability and decreased reliability in water supply.
- Benefit or reduce exposure from high market volatility, and minimise the impact of the cost-price squeeze.

Irrigation Optimiser can help growers achieve the aim by modelling the impact of alternative agronomic practices and whole-of-farm irrigation strategies on the trade-offs between whole-farm profitability ($/ML), economic risk and environmental outcomes for farm businesses across Australia. The development team has used eight case studies in NSW and Qld to validate the model.

How to use Irrigation Optimiser

To use the tool, you enter information about your own farm, such as:

- Farm description
- Water sources
- Crops you could grow
- Soil type
- Expected costs
- Expected prices

Based on your inputs, the Irrigation Optimiser displays the results (e.g. amount of water to apply to maximise profit over the whole farm) in a simple format in your web browser.

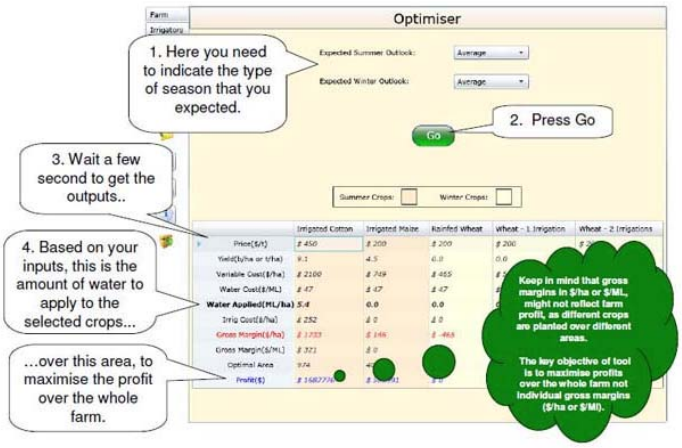


Figure 49. Example output from Irrigation Optimiser.

How to get it

The tool is web-based and is available at http://www.apsim.info/irrigationoptimiser/

For more information, contact Dr Daniel Rodriguez: Email: d.rodriguez@uq.edu.au or visit the Queensland Alliance for Agriculture and Food Innovation, The University of Queensland.

9.1.4 Rainman StreamFlow

Rainman StreamFlow is a decision-support tool that helps farmers to predict rainfall at a specific location within a specified time period and can be used to:

- Analyse records for individual locations for seasonal, monthly and daily patterns.
- Forecast seasonal rainfall based on the SOI or SST.
- Use group locations for spatial analysis.
- Import monthly, daily rainfall and streamflow data.
- Print results; see examples of tables, graphs, charts or maps.

Rainman StreamFlow is a software package that uses historical weather records to forecast seasonal rainfall and streamflow. Weather records used are from 3800 rainfall locations and 400 streamflow gauging stations. The forecasts are based on the Southern Oscillation Index and sea surface temperatures of the Pacific and Indian Oceans.

Historical rainfall, flow and climate data is included with Rainman StreamFlow but can be updated as follows:

- Rainfall: data for all stations can automatically be updated monthly via the internet for free.
- Streamflow data can be manually updated if required.
- Daily climate record updates are available via SILO by subscription.
- You can enter daily data for your own farm.

Outputs

Examples of outputs from Rainman Streamflow are shown in Figure 50 and Figure 51.

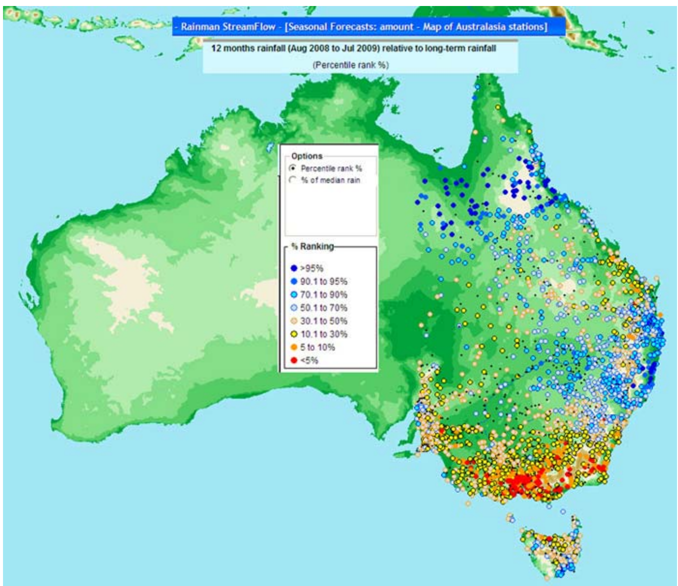
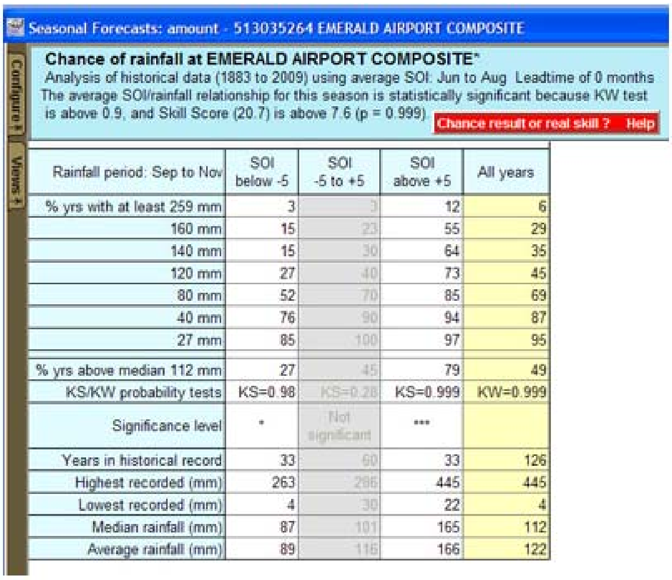


Figure 50. The chance of rain within the next 3 months at Emerald.



Seasonal Forecasts: amount - 513035264 EMERALD AIRPORT COMPOSITE

Chance of rainfall at EMERALD AIRPORT COMPOSITE*

Analysis of historical data (1883 to 2009) using average SOI: Jun to Aug Leadtime of 0 months
The average SOI/rainfall relationship for this season is statistically significant because KW test is above 0.9, and Skill Score (20.7) is above 7.6 (p = 0.999). Chance result or real skill ? Help

Rainfall period: Sep to Nov	SOI below -5	SOI -5 to +5	SOI above +5	All years
% yrs with at least 259 mm	3	3	12	6
160 mm	15	23	55	29
140 mm	15	30	64	35
120 mm	27	40	73	45
80 mm	52	70	85	69
40 mm	76	90	94	87
27 mm	85	100	97	95
% yrs above median 112 mm	27	45	79	49
KS/KW probability tests	KS=0.98	KS=0.28	KS=0.999	KW=0.999
Significance level	*	Not significant	***	
Years in historical record	33	60	33	126
Highest recorded (mm)	263	286	445	445
Lowest recorded (mm)	4	30	22	4
Median rainfall (mm)	87	101	165	112
Average rainfall (mm)	89	116	166	122

Figure 51. Rainfall in eastern Australia over the last 12 months.

How to get it

Rainman Streamflow is available on CD and is currently free. Email Ross Ballin, Department of Agriculture, Fisheries and Forestry (Queensland), for a copy of the CD. Email: ross.ballin@daff.qld.gov.au, Phone: 07 4688 1468

There is more information about the software on the QDAFF website currently at http://www.daff.qld.gov.au/26_15734.htm.

9.1.5 SILO

SILO is a tool for farmers, extension officers and developers of decision-making tools. It is a database of about 120 years of continuous daily weather records for Australia, which includes:

- Rainfall
- Temperatures (minimum and maximum)
- Radiation
- Evaporation
- Vapour pressure

The records are based mainly on observed data, with interpolation where there are data gaps. SILO data is up-to-date (near real time), in formats useful for farmers, researchers and policy-makers and is a data source for seasonal climate models and environmental forecasting models.

SILO includes climate data from around 3800 Bureau of Meteorology stations across Australia and it interpolates the data into a regular 5-km grid resulting in 350,000 grid squares.

You enter a location (weather station) and a date range. Then you select the data format you want (e.g. rainfall only, Rainman format), enter your subscriber details and the dataset is then delivered to you. The data does not include projections or analysis for a changing climate. It is simply a reference dataset.

How to get it

Users of SILO can subscribe and request/pay for data through their subscription. The website has a New Users section that describes how to navigate through the site. Subscribe via the BOM website.

9.1.6 The APSIM model

The APSIM model is not designed for use by farmers, but underpins other models such as Yield Prophet, WhopperCropper, HowOften? and HowWet. It is a powerful model and has the potential to be calibrated (parameterised) for vegetable crops. There is already a version that can be used with broccoli.

APSIM produces predictions of yield and other biological and physical processes within the farming system according to the climate, soil and management inputs. Figure 52 and Figure 53 show example outputs.

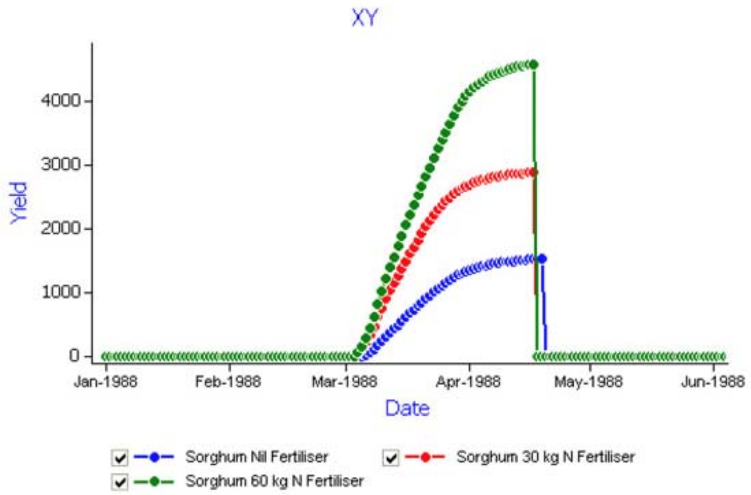


Figure 52. The predicted yield from a sorghum crop according to three levels of fertiliser input.

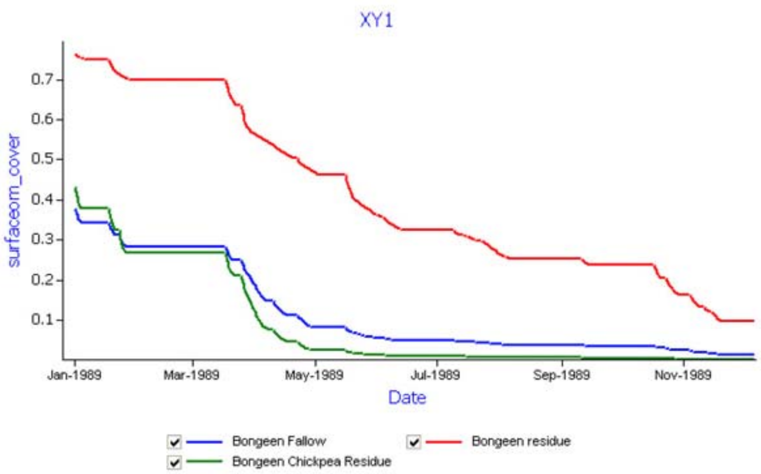


Figure 53. The effect of residue type on the speed of decomposition.

How to get it

The APSIM website: http://www.apsim.info/

Table 34. Tools available for managing climate across agriculture[135]

Tool	Topic	Commodity	Region	Cost	Web address
AfloMan	Aflatoxin contamination	Grains (peanuts)	All	Free	http://www.apsim.info/afloman/
APSFarm	Maximising farm profits	Grains, Beef, Sheep, Dairy, Cotton	All	Free	http://www.qaafi.uq.edu.au/
APSIM	Simulation model used in other tool	Grains	All	Free	http://www.apsim.info/
AusFarm	Mixed farming systems	Grains, Beef, Sheep	Temperate southern Australia	Annual licence fee	http://www.hzn.com.au/ausfarm.php
AussieGrass	Pasture growth outlook	Pastures	All grazing regions	Free maps	http://www.longpaddock.qld.gov.au/about/ researchprojects/aussiegrass/index.html
Australian CliMate™	Climate analysis tools	All crops	All	Free	http://www.australianclimate.net.au/ or download from the App Store.
Crop disease forecast	Crop disease forecasts and steps to take	Grains	Western Australia and, all of the southern grain production regions	Free	http://www.agric.wa.gov.au/PC_92989.html
CropMate	Climate and weather info to plan and manage your crop cycle	Crops	NSW, Qld, Vis, SA	Free	http://cropmate.agriculture.nsw.gov.au/
DairyMod	Simulation models	Beef, Sheep,	Temperate,	Free	http://www.publish.csiro.au/paper/EA07133

135 Rounding up climate tools for Australian farmers http://www.climatekelpie.com.au

Tool	Topic	Commodity	Region	Cost	Web address
	for whole pasture systems	Dairy	Mediterranean and subtropical regions		
EcoMod	EcoMod	Sheep, Beef	All		http://www.publish.csiro.au/paper/EA07133
Flowering Calculator	Flowering times and risk of frost and heat	Grains	Western Australia, South Australia (limited applicability)	Free	ian.foster@agric.wa.gov.au http://www.agric.wa.gov.au/
GRASP	Simulation model for grass	Beef, Sheep, Dairy	All	Free	Ken.A.Day@climatechange.qld.gov.au
GrassGro	Likely lambing/calving time, stocking rates, gross margins	Pastures (beef and sheep on sown pasture)	Southern Australia	One-off fee	http://www.hzn.com.au/grassgro.php
GrazFeed	Likely animal production, need for pasture feed	Pastures (beef and sheep)	Southern Australia – temperate and subtropical pastures	One-off fee	http://www.hzn.com.au/grassgro.php
HowOften?	Rainfall and run-off probabilities	Grains	All	Free	http://www.apsim.info/How/HowOften/how%20often.htm
HowWet?	Soil moisture	Grains	Regions where soil water and nitrate at planting are important	Free	http://www.apsim.info/How/HowWet/how%20wet.htm
Irrigation Optimiser	What to plant and how much water to use	All	Irrigated regions	Free	http://www.qaafi.uq.edu.au/

Tool	Topic	Commodity	Region	Cost	Web address
					d.rodriguez@uq.edu.au
Nitrogen Fertiliser Calculator	Nitrogen needs and likely yields	Grains (wheat and sorghum)	Queensland and northern New South Wales	Free	howard.cox@daff.qld.gov.au
Pastures from Space	Current and historical pasture growth rate	Pastures	Temperate and Mediterranean regions of southern Australia	Free or subscription fee	http://www.fairport.com.au/
Rain Forecaster	Rainfall probabilities and effect on yield	Sugar	Qld, North NSW	One-off fee	http://www.bses.org.au/
Rainman StreamFlow	Rainfall probabilities	All	All	Free	http://www.dpi.qld.gov.au/26_15734.htm ross.ballin@daff.qld.gov.au
Seasonal Crop Shire Yield Forecast	Likely seasonal shire yields	Grains	All major cropping regions	Outputs from the tool are free	http://www.dpi.qld.gov.au/fieldcrops andries.potgieter@dpi.qld.gov.au
SGS Pasture Model	Pasture models	All	All	Free	http://www.imj.com.au/consultancy/wfsat/wfsat.html bcullen@unimelb.edu.au http://www.publish.csiro.au/paper/EA02209.htm
SILO	Online climate database	All	All	Some free, some subscription fee	http://www.longpaddock.qld.gov.au/silo/
SYN [Select Your Nitrogen]	Nitrogen needs	Grains	Western Australia	Free	http://www.agric.wa.gov.au/ bbowden@agric.wa.gov.au

Tool	Topic	Commodity	Region	Cost	Web address
VineLOGIC	Bud-burst and flowering times; likely yields	Viticulture	All grape-growing regions	One-off fee	http://www.awri.com.au/ roxanne.portolesi@awri.com.au
WhopperCropper	Nitrogen needs and likely yields and gross margins	Grains	All major cropping regions	One-off fee	http://www.daff.qld.gov.au/ howard.cox@daff.qld.gov.au
Yield and N Calculators	Nitrogen needs and likely yields	Grains (cereal and canola)	Dryland regions in southern Australia	Free	http://www.clw.csiro.au/products/ncalc/index.html ncalculator-gw@csiro.au
Yield Prophet®	Yield potential	Grains (wheat, barley, sorghum, canola, oats)	All dryland and irrigated cropping regions	Subscription fee	http://www.yieldprophet.com.au/ yieldprophet@bcg.org.au

9.2 Tools for forecasting

The main reputable online sources of weather and climate forecasts for Australia are:

- Weather and warnings - Bureau of Meteorology
- Water and the Land (WATL) - Bureau of Meteorology
- Seasonal outlooks - Bureau of Meteorology
- Multi-week forecasts - Centre for Ocean-Land-Atmosphere Studies
- Multi-week forecasts - Bureau of Meteorology

9.2.1 Weather and warnings - Bureau of Meteorology

Weather forecasts, warnings and observations for Bureau of Meteorology weather stations across Australia.

How to get it

http://www.bom.gov.au/weather

9.2.2 Water and the Land (WATL) - Bureau of Meteorology

WATL (pronounced 'wattle') brings together climate and weather information for farmers, including forecasts for:

- rainfall – up to 8 days out
- rainfall – cumulative rainfall to date with potential season outcomes
- temperature
- wind
- pressure
- humidity
- evaporation
- sunshine
- El Niño and La Niña

How to get it

http://www.bom.gov.au/watl/

9.2.3 Seasonal outlooks - Bureau of Meteorology

Seasonal outlooks include:

- 3-month rainfall outlook – a description of the outlook for north, south-east and western Australia.
- 3-month rainfall outlook – maps and tables showing the chances of exceeding the median or of getting a certain amount.
- 3-month temperature outlook for north, south-east and western Australia.
- ENSO wrap-up – regular commentary on the El Niño - Southern Oscillation.
- ENSO outlooks – forecast of El Niño and La Niña events. A summary of the opinion of National Climate Centre climatologists on the outputs from eight reputable climate models.

How to get it

http://www.bom.gov.au/climate/ahead/rain_ahead.shtml

9.2.4 Multi-week forecasts – Centre for Ocean-Land-Atmosphere Studies

This site has the only multi-week forecast for Australia.

Temperature and rainfall outlooks:

- 0–5 day outlook
- 6–10 day outlook
- 10-day anomalies

How to get it

http://wxmaps.org/

9.2.5 Multi-week forecast – Bureau of Meteorology

The Bureau of Meteorology, with support from Managing Climate Variability, is developing an Australian-based multi-week forecast. The bureau will use the POAMA model for weather predictions, which should improve reliability especially for predicting extreme weather events.

The POAMA-based weather predictions will be 2–4 weeks ahead, making them especially useful to agriculture and water-management industries.

How to get it

http://www.bom.gov.au/watl/

9.3 Tools for understanding the climate

There are many tools and models available worldwide for helping people to understand how the climate is predicted to change and to make some specific predictions on what is expected, given different emission scenarios and interests.

9.3.1 Climate dogs

The Victoria DPI[136], NSW DPI[137] and the Bureau of Meteorology[138] have developed a series of 5 videos that explain how global climate processes vary their behaviour, potentially resulting in wetter or dryer seasons.

Climate dogs shows, in a very entertaining and accessible way, how climate drivers work by herding rain towards or away from NSW and Victoria. The five 'climate dogs', representing the climate processes, are Enso, Indy, Ridgy, Sam and Eastie.

ENSO = El Niño–Southern Oscillation or El Niño/La Niña–Southern Oscillation. Changes in Enso's behaviour have a significant influence on rainfall probabilities in inland NSW during the winter and spring period.

INDY = Indian Ocean Dipole (IOD). Like Enso, changes in Indy's behaviour also have a significant influence on rainfall probabilities in inland NSW during winter and spring.

136 Victorian Department of Primary Industries http://www.dpi.vic.gov.au/?a=51059
137 NSW Department of Primary Industries http://www.dpi.nsw.gov.au/agriculture/resources/climate-and-weather/variability/climatedogs
138 Bureau of Meteorology www.bom.gov.au

RIDGY = Sub-tropical Ridge (STR). Ridgy's position and intensity have a significant influence on weather in NSW. Recent changes in Ridgy's behaviour appear to be driving some significant changes to southern NSW rainfall patterns.

SAM = Southern Annular Mode. Recent changes in Sam's behaviour increase probabilities of rainfall in spring and summer in some parts of NSW.

EASTIE = East Coast Low. Eastie, better known as the East Coast Low, represents the deep low-pressure systems that are an important climate feature along the southeast coast of Australia.

These five sheepdogs love rounding up our rainfall. From a farmer's perspective, when they are well behaved they bring moisture from the oceans and allow it to fall over Victoria and NSW as rain, hopefully delivering the right amount at the right time. But they don't always work the way we'd like them to and can sometimes scatter the mob, effectively chasing rainfall away. Over recent decades some of these dogs have changed their behaviour, contributing to our extended dry spell and the changing weather patterns that many farmers have noticed.

How to get it

Visit Victorian Department of Primary Industries website at http://www.dpi.vic.gov.au/?a=51059 or the

NSW Department of Primary Industries http://www.dpi.nsw.gov.au/agriculture/resources/climate-and-weather/variability/climatedogs

9.3.2 OzClim

OzClim is the primary site for information on how the climate is predicted to change in the future. This site allows three levels of access to 13 different climate models, 8 different atmospheric greenhouse gas scenarios and rates of global warming to allow users to generate predictions that relate to areas all over Australia.

Step by Step access: This takes users though a simplified set of input criteria and generates a map showing the excepted changes in rainfall or temperature over the timeframe requested.

Examples: provides the expected changes to temperarture or rainfall from a simplied set of scenarios.

Advanced: Allows full access to the models and criteria with outputs such as maps, GIS data and spreadsheets, and also provides data specific to a large number of regions.

This is an excellent tool, which in summary can:

- Generate climate change scenarios in a few easy steps.
- Explore climate scenarios from 2020 to 2100.
- Guide you through the process of generating your own climate scenarios.
- Allow you to download maps and projections data for non-commercial research.

OzClim provides a simple step-by-step option to help you generate and explore climate scenarios. There are also six scenarios in the examples section for rainfall and temperature for 2035. The advanced section is designed for the scientific research community and policy-making. Choose from 23 climate models, eight emission scenarios and three climate sensitivities.

How to get it

http://www.csiro.au/ozclim

You will need to register to use the site, but once you have registered it is free.

9.4 Tools – carbon footprinting and managing emissions

9.4.1 Vegetable Carbon Calculator[139]

The Vegetable Carbon Calculator is a free tool that allows you to develop a carbon footprint of a vegetable farming operation. The tool was developed as part of a HAL project (VG09187), funded by Australian Vegetable Growers through HAL with support from Houston's Farms (Tasmania) and Woolworths.

The tool provides a framework and baseline data that growers can use to develop a carbon footprint for their own farming operation.

The Vegetable Carbon Calculator website also provides training materials on how to use the tool and some background information on concepts surrounding carbon and carbon footprinting.

How the tool works

The tool allows growers to develop their own carbon footprint and requires that data be entered under the following categories:

1. Energy
2. Waste
3. Fertiliser
4. Refrigerants used
5. Land use

Once this data is entered into the tool, it calculates a carbon footprint, which can then be exported from the calculator.

Assumptions, methodology and estimation of direct on-farm emissions

The methodology employed by the tool and assumptions and emissions factors are given in a protocol document, which is available for downloading on the calculator website[140].

There is very little data available on direct greenhouse gas emissions for vegetable crops in Australia. The research has not yet been completed to determine the actual emissions of nitrous oxide and carbon dioxide from Australian soils under local conditions and for various

139 http://www.vegiecarbontool.com.au
140 Vegetable Carbon Calculator Protocol. VG09187Australian vegetable industry carbon footprint tool: Satge 2. http://www.vegiecarbontool.com.au

crop management practices. The carbon vegetable tool developers have therefore used best-available estimates of these emissions from overseas research and data from other crops.

Direct nitrous oxide emissions from fertiliser addition have been calculated according to the guidelines published by the intergovernmental panel on climate change (IPCC) and a blanket emissions factor of 0.01 kg N_2O-N / kg N[141] has been used for direct nitrous oxide emissions resulting from both synthetic and organic fertiliser application. There is significant uncertainty inherent in this emission factor. Results will vary considerably with crop type, application rate and specific climate, amongst many other factors. Given that the Vegetable Carbon Calculator is designed as a general tool to be applied across a range of different vegetables and farming practices, it was deemed most appropriate to employ the general IPCC emissions factor. An Australian technique with State-specific data was used to estimate nitrous oxide emissions associated with leaching and run-off[142]. Fertiliser volatilisation is assumed to be 0.1 kg NH3-N + NOx-N per kg of synthetic fertiliser N applied and 0.2 kg NH_3-N + NOx-N per kg of organic fertiliser N applied[1].

The Vegetable Carbon Calculator website has two components:

1. The vegetable carbon calculator.
2. Vegetable industry carbon education materials.

The education materials were funded by Woolworths and HAL. The calculator was based on the Houston's Farms Footprinting Tool, which was made available to the project development team.

How to use the tool

In order to estimate your on-farm carbon footprint, you will need to have the following information available for the year for which you want to calculate the carbon footprint of your farm:

- Electricity bills/meter records for the reporting year.
- Fuel bills/receipts for the reporting year (i.e. natural gas, petrol, diesel, LPG, wood).
- Records of waste processed on-farm for the reporting year.
- Records of fertiliser usage for the reporting year.

141 2006 IPCC guidelines for national greenhouse gas inventories, Volume 4: Agriculture, forestry and other land use, Prepared by the national greenhouse gas inventories programme, Eggleston, H.S., Buenida, L., Miwa, K., Ngara, T. And Tanabe, K. (eds). www.ipcc.ch. Accessed: September 2010

142 Australian national greenhouse accounts, National inventory report 2008, Volume 1. www.climatechange.gov.au. Commonwealth of Australia. Accessed: September 2010.

- Service documents for on-site cold rooms or industrial freezers for the reporting year.

Output from the tool

The tool can provide four specific outputs:

- Farm footprint for your farm in the year(s) for which data was entered.
- Update crop types: compare the various crops by years.
- Emissions per crop: calculated the emissions attributable to various crops grown.
- Comparisons per crop: provides a benchmarking comparison of emissions with other users of the tool for the year in question.

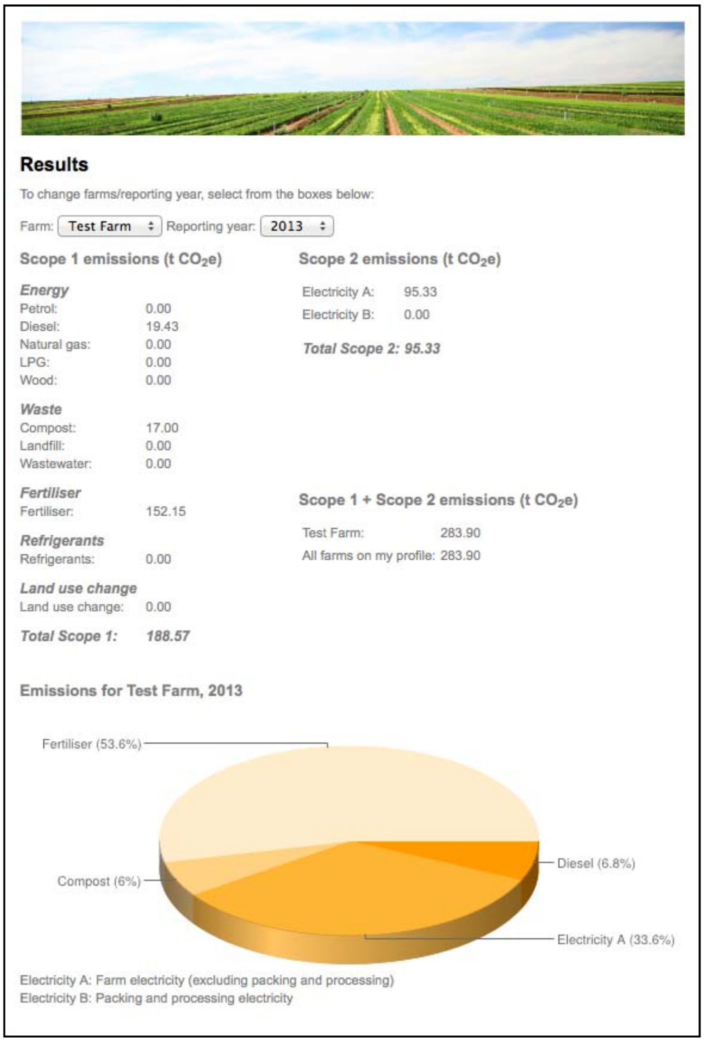


Figure 54. Example of carbon footprint.

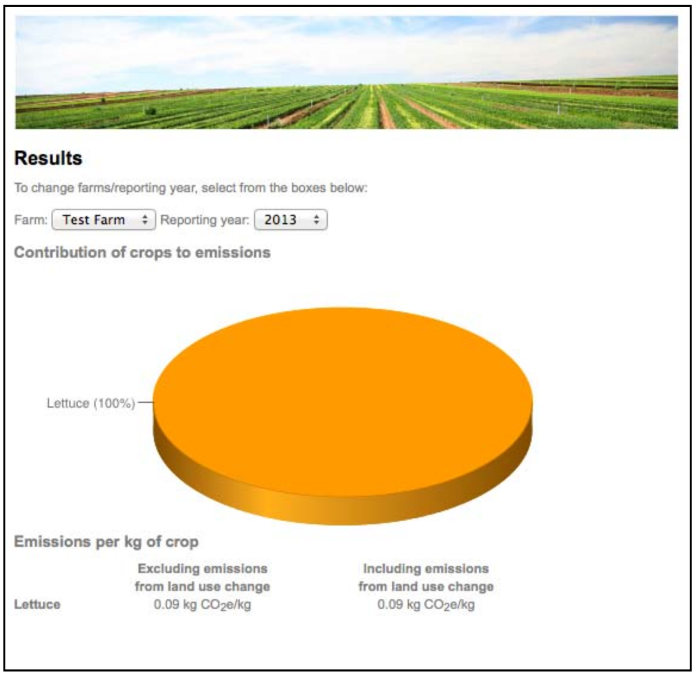


Figure 55. Example of crop contribution to CO2-e emissions.

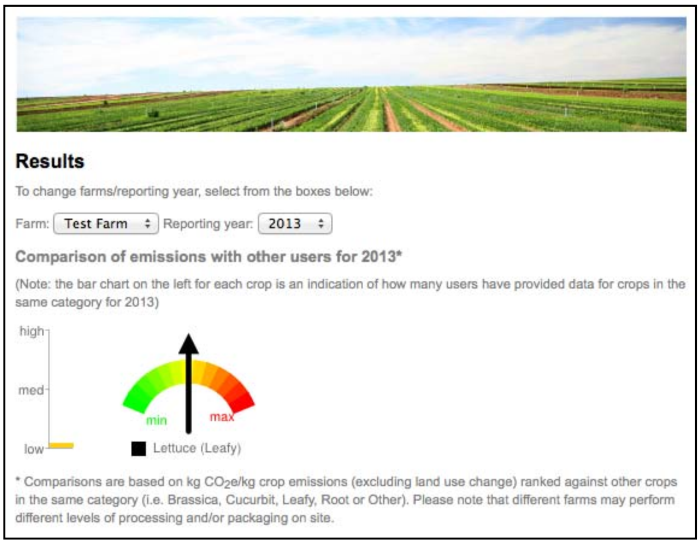


Figure 56. Benchmark comparison with other users of the Vegetable Carbon Calculator.

Note: There is no legislative requirement for vegetable farming operations in Australia to develop carbon footprints for their farms or to report their emissions, and this is unlikely to change in the foreseeable future.

How to get it

The tool is available from the website: http://www.vegiecarbontool.com.au

9.4.2 Cool Farm Tool

The Cool Farm Tool (CFT) is a greenhouse gas calculator that is free for growers. It can help them measure the carbon footprint of crop and livestock products.

The tool is currently being used by the Australian processing tomato industry. It is also being used worldwide by:

- Unilever (tomatoes)
- Costco (eggs)
- Pulse Canada (navy beans)
- GIZ and Sangana (coffee)
- Heinz (tomatoes)
- Oxfam (Broccoli)

The CFT was originally developed by Unilever and researchers at the University of Aberdeen to help growers measure and understand on-farm greenhouse gas emissions. The tool is designed to be simple to use but scientifically robust in the complex arena of carbon accounting. The CFT has been tested and adopted by a range of multinational companies that are using it to work with their suppliers to measure, manage, and reduce greenhouse gas emissions in the effort to mitigate global climate change.

The CFT is a farm-level greenhouse gas emissions calculator based on empirical research from a broad range of published data sets. It is designed to be approachable and easy to complete, using information that a farmer will have readily available. The tool identifies hotspots, makes it easy for farmers to test alternative management scenarios and identifies those that will have a positive impact on total net greenhouse gas emissions. Unlike many other agricultural greenhouse gas calculators, the CFT includes calculations of soil carbon sequestration, which is a key feature of agriculture that has both mitigation and adaptation benefits.

The CFT was vetted, improved and adapted over two years (2010-12) through the global farming assessment Cool Farming Options, led by the Sustainable Food Lab in conjunction with University of Aberdeen and Unilever. Cool Farming Options was supported by 17 sponsoring partners and involved CFT pilots in 16 crops, in 15 countries. The project had an additional eight non-sponsoring partners with pilots in seven other countries and six other crops.

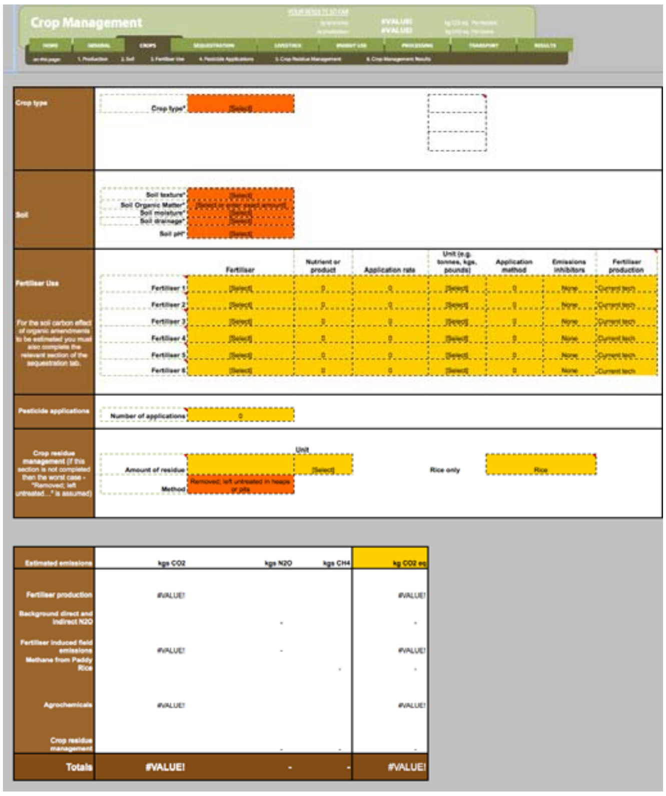


Figure 57. Screenshot of the Cool Farm Tool.

How to get it

The Cool Farm Tool is available from http://www.coolfarmtool.org

9.4.3 FarmGAS Tool

The FarmGAS Scenario Tool enables farmers, researchers and advisors to investigate how different management and production practices might alter the greenhouse gas emissions profile of their enterprise or farm.

Features of the tool include the ability to change emission factors, alter production details such as feed factors for livestock, change the stubble management of crops, and select a different manure management system.

The FarmGAS Scenario Tool was developed with funding from the Australian Government's Climate Change Research Program and Meat & Livestock Australia. FarmGAS is not government-endorsed or approved, including for use under the Government's Carbon Farming Initiative (CFI).

How to get it

http://calculator.farminstitute.org.au

9.4.4 Australian Wine Carbon Calculator

This tool estimates total emissions of carbon dioxide produced as a result of the activities related to wine industry businesses, such as vineyards, wineries and transport companies. Coverage of the tool (e.g. fuel types and business activities) has been selected as being specific to the wine industry. While the form of the tool has been adapted from the International Wine Carbon Calculator, the key technical references for development of the calculator are:

- National Greenhouse Accounts (NGA) Factors, July 2012
- National Greenhouse Accounts (NGA) Factors, July 2011
- National Greenhouse and Energy Reporting Act, 2007 (and associated regulations and technical guidelines)

The Australian Wine Carbon Calculator was launched in April 2009 to help Australian wineries measure their carbon footprint. The project was a joint initiative of WFA, the South Australian Wine Industry Association and the Winegrape Council of SA.

The Australian calculator builds on the international version that has been in use since early 2008 and includes components specific to Australian needs, such as Australian Government-endorsed emission factors. WFA was part of the international group that developed the initial calculator. The Australian calculator is comprehensive, requiring even more data than is needed under the Government's National Greenhouse and Energy Reporting Scheme (NGERS). However, an output sheet has been included that collates the subset of data needed to complete NGERS.

Either the Australian Wine Carbon Calculator or the NGERS calculator tool can be used to report a carbon footprint for Entwine Australia Membership and Preliminary Membership. The NGERS calculator does not account for scope 3 (packaging) emissions so those using NGERS will also need to use the Australian Wine Carbon Calculator for reporting scope 3. If using the Australian Wine Carbon Calculator, you are only required to complete the scope 3 packaging worksheet (green tab numbered 9) in the calculator.

The Australian Wine Carbon Calculator is an Excel-based tool, useful for estimating emissions from vineyards, wineries and/or packaging and distribution. It provides general guidance on the significant emissions associated with individual products, but is not sufficient for product-level lifecycle analysis (which is required to claim 'carbon neutrality').

How to get it

http://www.wfa.org.au/entwineaustralia/carbon_calculator.aspx

9.4.5 Nursery industry energy calculator

The Australian nursery industry in collaboration with the University of Southern Qld has developed a renewable energy calculator. The tool is based on the EnergyCalc[143] tool that was developed by the National Centre for Engineering in Agriculture, University of Southern Queensland.

The Renewable Energy Calculator is available online via the NIAA website[144] and is free. The tool was designed for use by the nursery industry but would also be useful for vegetable growers. The tool will help calculate the current energy load within a business and calculate the renewable energy required to offset the energy cost.

This Renewable Energy Calculator is designed as a simple and easy-to-use tool to assess the approximate costs and savings associated with installing solar panel arrays and wind generation systems. Users can assess savings of purchased electricity and opportunities to sell to the grid.

Currently the Federal and State Governments offer a number of incentives for small-scale implementation of renewable energy systems. These include rebates and tax incentives, Renewable Energy Certificates (RECs), and Feed in Tariffs (FiTs) when connecting and supplying generated electricity to the electricity grid from a small generation unit (SGU), such as solar, wind, hydro etc.

State schemes and FiTs differ from State to State and are reviewed from time to time. Thus, the savings generated by supplying renewable energy to the electricity grid will vary depending on the State in which you operate. Your choice of electricity retailer will also impact on the savings you gain, as a supplier is able to provide payments above those mandated in the FiT for renewable energy sold to the grid.

To use the Renewable Calculator some data is required. You will need access to 12 months of electricity bills. You then choose the type of system (solar or wind) to consider and the amount (%) of currently purchased electricity to be replaced with a renewable energy SGU. A nearby weather station is then selected for local wind-run and solar exposure information. The approximate size of the SGU is then calculated. Approximate capital and operating costs are provided but should be adjusted based on local supplier information. Finally, a monthly comparison of energy demand versus generated electricity from your SGU is produced. Electricity costs before and after installation are also provided, together with a benefit/cost assessment and payback period.

Some examples of the outputs from the Renewable Energy Calculator are shown below in Table 35 and Figure 58.

143 http://kmsi.nceaprd.usq.edu.au/
144 Renewable Energy Calculator http://www.energycalc.ngi.org.au/

Table 35. Example of a renewable power generation system [145]

Items	Details
System Type	Wind
Wind Turbine	3000W Turbine
Number of Turbines	3
Tower Height	10 m
Maximum Rated Power	
System Lifetime	25 year
Capital Cost	$69000
Operating Cost	$1380 per year
Electricity Sale Price*	$0.44 per kWh
Electricity Purchase Price	$0.2 per kWh
Energy Demand	18000 kWh per year
Energy Generated	21373 kWh per year
Greenhouse Gas Emissions Reduced**	18828 kg per year

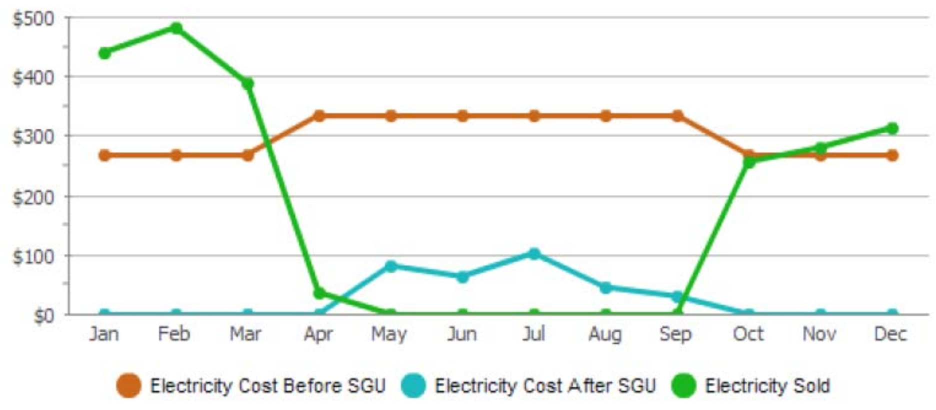


Figure 58. Economic analysis of variable cost savings using renewable energy[146]

How to get it

http://www.energycalc.ngi.org.au

[145] NGIA Renewable Energy Calculator User Manual
[146] NGIA Renewable Energy Calculator User Manual

9.5 Tools for financial management

9.5.1 Veg Tool: Gross Margin Comparison Tool for Vegetables

The Veg Tool was developed for the Australian vegetable industry by Schofield Robinson, with funding from the Australian vegetable industry and HAL.

The tool is not specifically related to assessing the impacts of climate change but it does provide the framework for developing realistic gross margins for Australian vegetable growers and can be used to compare various scenarios.

The program allows growers to enter estimated yields, prices and input costs in familiar units, e.g. without having to convert everything into "per hectare" values, to arrive at a gross margin. Users can decide on the level of accuracy, but it is envisaged that the main use of the tool will be to conduct relatively simple comparisons of different crop production scenarios. The tool can be used to evaluate the financial impact of adopting some of the climate change adaptation measures suggested in this report, and could be used in conjunction with the Vegetable Carbon Calculator to assess the financial impact of reducing the carbon footprint of a vegetable farm.

The value comes from being able to input data that applies to individual farms, and so will be much more accurate than using generalised gross margins for particular crops.

For ease of use, a limited number of cost categories were included:

- Seed & Plants
- Fertiliser
- Fuel
- Chemicals
- Water
- Labour
- Electricity/Gas
- Packaging
- Freight/Transport
- Other Operating Costs

How to get it

The Veg Tool can be downloaded from the AusVeg website: http://ausveg.businesscatalyst.com/Default.aspx?PageID=3667793&A

9.6 Tools to assist with compliance

*Vegetable growers do not have to report emissions. Larger vegetable industry suppliers or processors may be required to report emissions. Overall industry emissions are estimated by the National Carbon Accounting System (*NCAS) *to produce Australia's National Greenhouse Accounts and reported internationally.*

As agriculture is not covered by the emissions trading scheme, vegetable growers are not required to report emissions under the National Greenhouse and Energy Reporting scheme (see the VG12049 project report for details of the legislation and regulations).

For those vegetable industry suppliers or processors that are a liable entity, reporting will be required under the National Greenhouse and Energy Reporting scheme, administered by the Clean Energy Regulator[147].

The following compliance tools are available on the on the Clean Energy Regulator website.

9.6.1 Threshold estimator and user guide

The threshold estimator (XLS 5.12 mb) is a tool to assist users to self-assess if:

- An individual is likely to be a liable entity under the Clean Energy Act 2011 (the Clean Energy Act); and/or
- A controlling corporation is likely to have obligations to register and report under the National Greenhouse and Energy Reporting Act 2007 (NGER Act).

The threshold estimator can be used to obtain an estimate of covered emissions, scope 1 and scope 2 greenhouse gas emissions, energy production and energy consumption, based on data entered by the user.

9.6.2 Solid waste calculator and user guide

The solid waste calculator (XLSX 2.23 mb) has been designed to aid corporations and others to assess the greenhouse gas emissions from landfill operations. This is done in accordance with the NGER Regulations 2008 and the methodologies of relevant parts of Chapter 5 of the NGER (Measurement) Determination 2008. It is applicable for the 2008–09 to 2011–12 NGER reporting years. The calculator also helps entities to estimate the release of legacy and non-legacy emissions from landfills.

147 http://www.cleanenergyregulator.gov.au

If you need further information about using the solid waste calculator, or the National Greenhouse and Energy Reporting and Clean Energy requirements in relation to emissions from landfill activities, refer to the NGER solid waste disposal on land 2.2 (PDF 3.8 mb).

9.6.3 NGER wastewater (Domestic and Commercial) calculator

The NGER domestic and commercial wastewater calculator is designed to aid corporations and others to assess the greenhouse gas emissions resulting from the treatment of domestic and commercial wastewater. This is done in accordance with the NGER Regulations 2008 and the methodologies of relevant parts of Chapter 5 of the NGER (Measurement) Determination 2008. The calculator is applicable for the 2008-09 to 2011-12 NGER reporting years.

9.6.4 NGER wastewater (Industrial) calculator

The NGER industrial wastewater calculator is designed to aid corporations and others to assess the greenhouse gas emissions resulting from the treatment of industrial wastewater. This is done in accordance with the NGER Regulations 2008 and the methodologies of relevant parts of Chapter 5 of the NGER (Measurement) Determination 2008. It is applicable for the 2008-09 to 2011-12 NGER reporting years.

9.6.5 Uncertainty calculators and user guides

The uncertainty calculators have been designed to assist registered corporations in assessing and reporting the uncertainty associated with their scope 1 greenhouse gas emissions under the NGER scheme. The calculations and factors incorporated in the calculators are in accordance with the National Greenhouse and Energy Reporting Regulations 2008 and the methodologies of Chapter 8 of the National Greenhouse and Energy Reporting (Measurement) Determination 2008.

The calculators have been developed to streamline data entry for reporting in the Online System for Comprehensive Activity Reporting (OSCAR). Registered corporations should note that they can use OSCAR to populate the NGER uncertainty calculator tool once all emissions and energy data has been entered into OSCAR.

9.7 Tools required

9.7.1 APSIM-based models

There is potential to make more of the mechanistic APSIM models that are being used by other industries to model predicted changes to crops in response to climate change.

Examples of models based on APSIM include:

- GrassGrow – pasture model.
- AussieGrass – pasture model.
- Dairy Mod – dairy/pasture model.
- MLA – future climate modelling for the livestock industry.

The vegetable industry could focus on two main activities in this area:

1. Model future scenarios, looking at sowing times, and the effectiveness on yield and profitability of various adaptation strategies to climate change.

2. Support elevated CO_2 work on new varieties to see how they will respond to higher CO_2 levels, investigate pest and disease interactions and play a role in the breeding of new varieties. Modelling would play a crucial role in these activities.

9.7.2 Tools to evaluate the suitability and risks of vegetable crop x growing region

There is a need to develop a tool that growers across Australia can use to evaluate how their crops will perform in the future.

Such a tool could be developed using the GIS formatted output from OzClim[148] matched to crop growing requirements, temperature and rainfall sensitive stages.

9.7.3 Forecasting of extreme events

The prediction of extreme weather events would be a considerable benefit to the vegetable industry in Australia. The Managing Climate Variability[149] project would be ideally suited to work with the Australian vegetable industry and the Bureau of Meteorology to improve forecasting in vegetable growing regions. The bureau is changing from statistical models to the POAMA model, which is better suited to this type of forecasting and considerable gains in this area are now possible.

148 http://www.csiro.au/ozclim
149 http://www.managingclimate.gov.au/

10 Conclusions

Industry level issues

The Australian vegetable industry is a relatively small emitter of greenhouse gases due to its small total area of cultivation (about 110,000 ha). The greenhouse gas emissions from the sector have been estimated at between 1.0 and 1.1 MT CO_2-e/year from direct and indirect emissions. The total emissions for horticulture are only 1% of agriculture or 0.12% of the national total. Vegetables are even less, at 0.05% of total emissions.

The vegetable sector has a very low rate of emissions per $ of value produced, about 85 t CO_2-e for every $1M in revenue generated (at the farm gate). These figures are low relative to other rural industries. For example, beef cattle emits 6686 t CO_2-e for every $1M in revenue, and sheep 3513. The big polluters such as power generation and aluminium emit 9945 and 7357 t CO_2-e for every $1M in revenue respectively.

The industry is characterised by a high level of inputs and management. This results in a high average greenhouse gas intensity of about 9.2 t CO_2-e per hectare per year, ranging from 7.5 for peas to 15.4 for capsicums. This emissions intensity is high compared to broad acre crops such as wheat.

Vegetable producers are big users of electricity for pumping and cooling. These emissions are counted in the electricity generation pool and not allocated to agriculture directly. Direct emissions from farms come mainly from nitrous oxide emitted from soils due to high usage of nitrogenous fertiliser and water.

The vegetable industry is an efficient user of irrigation water, both in terms of ML per tonne of crop produced, and per $ value of production. Both of these attributes mean the vegetable industry is in a strong position to compete with other water users in times of drought.

Weather variability

The most significant issue will be the predicted increase in the variability of the climate, especially temperature, and an increase in the frequency of extreme weather events. Rainfall patterns will be affected slightly and become more variable, but total rainfall amounts will not change significantly.

Briefly, some of the expected regional changes are:

- Gatton, Qld: the most variable times for this region are for minimum temperatures in midwinter and for maximum temperatures in spring and summer.
- Hay, NSW: the greatest variability in this region will be in maximum temperatures in

spring, summer and autumn.

- Werribee, Vic: the greatest variability will be in minimum temperatures throughout the year and maximum temperatures in spring and summer.
- Murray Bridge, SA: the greatest variability will be in minimum temperatures in summer, autumn and winter, and maximum temperatures in summer.
- Manjimup, WA: the greatest variability in this region will be the spring and summer maximum temperatures.
- Devonport, Tas: the greatest variability will be minimum temperatures in summer and autumn.
- The seasonality of frosts has already changed over the last 20 years. Analyses have revealed that in eastern Australia the frost window is both starting earlier (on average up to 10 days earlier by 2010) and ending later (up to 46 days later by 2010).

There is some potential to counter the expected changes in average temperature by selecting new varieties or taking advantage of breeding that is underway, but this is unlikely to help with the predicted increase in variability.

There are also likely to be new challenges arising from a sustained increase in winter minimums. For example, pests and diseases that were previously unable to overwinter may now become problematic more often and earlier in the season.

Tools

There is a range of tools available to help growers manage climate variability and change, and these come under the following categories:

1. Managing climate
2. Forecasting
3. Understanding the climate
4. Carbon footprinting
5. Financial management

The most promising tools in each category are described in the review.

There exists an excellent series of five animated videos called *The Climate Dogs.* They describe in an easy-to-understand way, how the climate is changing and are well worth viewing.

There is a carbon footprinting tool called the Vegetable Carbon Calculator that can be used to calculate the carbon footprint of individual farms. However, the data underlying some of the assumptions on soil emissions needs to be verified by field experimentation.

Direct impacts of CO_2

Higher CO_2 levels will have some direct benefits on growth rate, but in many cases will not result in significantly higher yields. The higher CO_2 will reduce crop water requirements, making them more drought-tolerant. Protected cropping has great potential to help manage variability, provided the economics and emissions status are acceptable to industry.

Adaptation and mitigation

Adaptations with the greatest potential to help in the short term include:

- Varieties and adapting planting schedules to accommodate expected temperature shifts.
- Use of irrigation to manage temperature extremes (low and high).
- Reconsideration of cooling practices.
- Low-cost protected cropping / shade.
- Developing resilience in the production system to withstand weather events e.g. increase soil water holding capacity of sandy soils.

The main mitigation options are:

- Reducing energy use and inputs costs through improved efficiencies in pumping, cooling and on-farm power generation.
- Reducing nitrous oxide emissions from soil through better nitrogen management, nitrification inhibiters and alternative nitrogen sources.
- Sequestering carbon in soils.

All of the mitigation and adaptation activities require further research to provide data relevant to the Australian vegetable industry.

Major economic impacts are likely, due to the scarcity (high cost) of irrigation water during droughts and direct effects of high temperature on yield and quality. The cost savings from implementing energy efficiencies present a positive, though relatively minor, opportunity.

In the final analysis, the Australian vegetable industry is in a strong position to meet the challenges of a changing climate but it must be prepared to meet these challenge head on, minimise negative impacts and make the most opportunities to ensure the industry continues to prosper into the future.

11 Appendices

11.1 Appendix: Literature review of greenhouse gas emissions from sustainable cropping systems of relevance to vegetable production

The impacts on greenhouse gas emissions of conventional and sustainable agronomic practices have been extensively researched and reviewed in broad acre agriculture. However, there have been few similar studies in horticulture.

Horticultural production in Australia occupies about one million hectares, and due to the high level of inputs such as irrigation water, nutrients and cultivation, it is likely to be responsible for much higher greenhouse gas emissions per unit area than broad acre agricultural cropping or grazing.

Soil organic carbon (SOC) is a large potential sink for sequestering C on a global scale (Komatsuzaki & Ohta 2007). The C sink capacity of the world's agricultural and degraded soils is 50-66% of the historic C loss or 42-72 Pg (1 Pg=10^{15} g). Apart from its C sequestering potential, SOC helps to sustain fertility and conserve soil water quality. And organic C compounds play a vital role in the nutrient, water and biological cycles.

The significance of this terrestrial C sink in agriculture is well recognised, and was a major focus of recent Australian Department of Agriculture, Fisheries and Forestry *Action on the ground* and *Filling the research gaps* initiatives.

No-tillage practices, cover crop management and manure applications all have potential to enhance SOC as well as contribute to sustainable food production and soil quality. The added benefit of sequestering carbon as a SOC is the associated improvements in soil health and consequently crop productivity. A potential negative aspect of building SOC levels is that this can be at the expense of increasing emissions of non-CO_2 greenhouse gases (Komatsuzaki & Ohta, 2007). In horticulture, soil C sequestration and greenhouse gas emissions can be strongly influenced by the modifying the impact of irrigation (Grace, 2008).

Minimum tillage and soil carbon

In Australian dry land agriculture, reduced tillage is aimed primarily at improving soil moisture retention. The practice has been widely adopted and uptake has continued to increase over the last 20 years. While there is now data to also support the use of minimum tillage for C sequestration in soils, this can be difficult to achieve due to the impact of high temperatures and variable rainfall.

Conservation tillage systems, including no-till, leaves more organic residue on the soil surface because the soil is not turned over (Komatsuzaki & Ohta, 2007). The organic matter is retained in stratified soil layers, with highest concentrations nearer to the surface due to the lack of soil disturbance. Stratification of layers can be reduced in no-till situations by selecting crops with deeper roots.

Crop trash retention alone does not necessarily result in improved SOC. A long-term (60-year) study from a wheat soil in Oregon, USA, showed how soil C could be maintained when stubble was retained and cultivated in with 111 kg ha^{-1} $year^{-1}$ of N supplied as organic manure. This contrasted with a steady decline in SOC when the residue was burned, cultivated in with no added N or cultivated in with the addition of 90 kg ha^{-1} $year^{-1}$ of inorganic N. The critical factor was the gradual mineralisation of organic N, and therefore the greatly reduced losses of N through leaching of NO_3. Furthermore, higher C:N ratios in soils with higher SOC reduced the availability of N, only gradually making it available (Komatsuzaki & Ohta, (2007). Another example is: after 12 years of no-tillage under a maize-soybean rotation in southern Illinois, the top 75 cm of soil showed that a no-till system sequestered 0.71 Mt ha^{-1} $year^{-1}$ more SOC than by mouldboard ploughing and 0.46 Mt ha^{-1} $year^{-1}$ more SOC than by chisel ploughing (Olson *et al*, 2005).

There are also limits to the amount of SOC that can be retained. Soils lose SOC more readily as the SOC content increases (Komatsuzaki & Ohta, 2007). In a Japanese soya sweet-corn rotation, a variety of steady-state systems produced a balance between C input and mineralisation within five years.

Yan *et al* (2007) showed that practising no-tillage on 50% of China's arable land and returning 50% of the crop residue to the soil would lead to an annual soil sequestration of 32.5 Tg of C, or about 4% of China's annual emissions for that year. This effect was expected to persist for 20-80 years. Metay *et al* (2007) found that in *Cerrado* soils in Brazil, in the top 10 cm of soil, no-tillage resulted in a net benefit of 350 kg of C sequestered per year compared with conventional tillage (offset discs to 15 cm).

Minimum tillage and greenhouse gas emissions

Manipulating tillage systems has great potential for reducing CO_2 emissions in agricultural cropping (Govaerts *et al*, 2009). Cultivation causes increased fluxes of CO_2 by increasing soil aeration and microbial activity that converts SOC into CO_2 (Komatsuzaki & Ohta, 2007). The highest fluxes of CO_2 occur in moist soils immediately after tillage. While individual experimental results vary, it is widely accepted that CO_2 emissions from cultivated soils are greater than those from uncultivated soils. Models have been developed to describe short-term soil C losses after tillage.

Six *et al* (2004), found that greenhouse gas mitigation through adoption of minimum tillage is complex and significant benefits are likely to occur in the long term. The importance of N_2O was much greater than previously thought and a better understanding of the role of N management was required before any definitive answers could be given on the net benefit of no-tillage.

N_2O emissions under conservation tillage are also influenced by the form of nitrogenous fertiliser applied. Venterea *et al* (2005) found a significant reduction in N_2O emissions after broadcasting urea or applying anhydrous ammonia to a minimum tillage but little difference in emissions between cultivation methods when N was applied as urea or ammonium nitrate.

In a corn-soybean rotation in Midwest USA, in the short-term (2 years), no tillage resulted in lower emissions of CO_2 than conventional methods involving heavy cultivation (mouldboard or chisel ploughing). Nearby, in a similar study, Ussiri & Lal (2009) found the trend was still the same after 43 years, with about 70% less SOC remaining after mouldboard or chisel plough cultivation and approximately 24% higher average daily CO_2 emissions compared with no tillage.

In Denmark, in loamy sand planted to spring barley, Chatskikh and Olesen (2007) found during a 113-day trial, that no-tillage reduced emissions of both CO_2 (about 25%) and N_2O (about 50%), compared with full conventional tillage.

Liu *et al* (2007) analysed soil cores in a laboratory and found higher fluxes of N_2, N_2O and CO_2 from the no-till soil than from conventional tillage. Ammonium N increased emissions of N_2 and N_2O compared with nitrate N, when soil moisture exceeded 60% water-filled pore space. N emissions continued to increase as soil moisture increased, presumably under anaerobic denitrification.

The finding by Lui *et al* (2007) supports the idea that when uncultivated soils become poorly aerated, anaerobic soil microbial activity is promoted and can lead to a reduced rate of oxidation of SOC to CO_2. Anaerobic soil conditions favour denitrification and the production of N_2O. Anaerobic conditions can also favour the production of CH_4 and means that reduced tillage aimed at increasing SOC levels risks causing greater fluxes of N_2O and CH_4 from the soil if anaerobic conditions are created (Komatsuzaki & Ohta, 2007).

Depth of fertiliser placement can also be a factor in greenhouse gas emissions. In a three-year wheat-corn-soybean field study in Canada, Drury *et al* (2006) found N_2O emissions were lower when the N fertiliser was placed deeper in the soil. This finding was supported by long-term results of a similar study by Liu *et al* (2006) under continuous maize cropping on a Colorado clay soil which showed lower nitrogen oxide (NO) and N_2O emissions at 10-15 cm compared to very shallow placement at 0-5 cm. CO_2 and CH_4 emissions were not affected by the depth of nitrogen placement.

Soil organic matter content may also modify greenhouse gas emissions. In soil with very high organic matter content, cultivation had no effect on CO_2 or CH_4 emissions while N_2O

emissions were greater in cultivated soils, all at the same moisture content (Elder & Lal, 2008).

Studies into the impact of cultivation on CH_4 emissions have found either no effect of cultivation on CH_4 emissions, or no-till causing an increase in emissions (Omonode *et al*, 2007). The determining factor is most likely the impact on soil aeration since anaerobic soil conditions favour CH_4 formation.

Modelling of carbon sequestration and greenhouse gas emissions

The CENTURY model can be used to model soil C, N, S and P dynamics, and it has been used more recently to estimate C sequestration under full-tillage and no-tillage situations. This model shows a good correlation between observed and predicted SOC sequestration (R^2=0.83), and that a reduction in tillage intensity results in greater C sequestration in a Mediterranean semi-arid agro ecosystems (Alvaro-Fuentes *et al*, 2009).

The DAYCENT model is a daily version of the CENTURY. It was developed more recently and is being used by the intergovernmental panel on climate change (IPCC) to estimate direct and indirect N_2O emissions for major cropping systems in the USA. It can be used to model fluxes of all three major greenhouse gases. Del Grosso *et al* (2005) used the DAYCENT model to evaluate major cropping across the USA and, including machinery emissions, the study found that conversion to no-tillage would lower the US national agricultural emissions by 20%.

La Scala Jr *et al* (2008) developed a first-order decay model that uses the decay rate of C in cultivated and uncultivated soil, together with the amount of labile C added, to predict CO_2 fluxes to a high degree of accuracy (R^2=0.97).

Clay mineralogy in those soils with a significant clay component appears to play a key role in determining the extent to which SOC can be sequestered under conservation tillage (Denef *et al*, 2004). In fact, the Rothamsted soil C model uses the clay fraction of soils to estimate changes in soil C. Therefore soils that have higher clay content also have a higher propensity to store C.

Impact of machinery emissions

Very few studies appear to incorporate emissions from machinery in CO_2 calculations. A Croatian study looking at wheat, soybeans, barley and maize compared conventional full tillage with no-till and found that across all crops total CO_2 emissions, including those from machinery, were reduced by around 88% for no-tillage systems (Filipovic *et al* 2006). This indicates that although CO_2 emissions can sometimes be higher under no-tillage, when emissions from machinery are taken into account, overall CO_2 emissions are higher for tillage cropping systems.

Organic mulches and manures

Adding manure to soils can lead to increased CH_4 and N_2O emissions (Yagi, 2002). Good management, such as avoiding excessive manure application and optimizing the application timing to synchronize with crop uptake, can reduce this negative impact on greenhouse gas emissions and maximise the positive effects of manure addition on SOC storage (Johnson *et al,* 2005).

Cover crops

Cover crops are a critical tool for sustainable soil management because they can scavenge soil residual N and help to establish an optimal N cycle (Komatsuzaki & Ohta, 2007). Grain cover crop residues have high C:N ratios and yield large amounts of litter, which can increase the soil organic matter content. Leguminous crops also produce considerable litter, but their residues have lower C:N ratios. Brassica crops produce small amounts of litter and the C:N ratio of their residues is low. These low C:N residue-producing crops result in quick decomposition of residues in the soil (Komatsuzaki, 1999). This supports the idea that intensive vegetable-producing soils have a greater capacity to sequester SOC than most field crops, despite the relatively small production area compared to broad acre crops.

The effect of cover crops on N_2O emissions depends more on the N application rate than form or timing. (Jarecki *et al*, 2009). High-yielding vegetable crops usually require more nutrients to be present in the soil than can be absorbed. Even where only organic manures are used to produce a high-yielding crop, nutrients are usually provided in excess of requirement. This leads to excessive nutrient leaching, particularly of $NO_{3,}$ and potential N_2O production. In such situations as this, the use of cover crops becomes an even more attractive alternative, since they can prevent N leaching or emission by accumulating excess soil N (Wagger and Mengel 1988, Gu *et al*, 2004).

Leguminous cover crops may prove very useful because they have the potential to fix atmospheric N, thereby reducing or eliminating the need to supply N. This reduces the demand for synthetic nitrogenous fertilisers that are manufactured using fossil fuels and therefore reduces CO_2 emissions associated with fertiliser manufacture.

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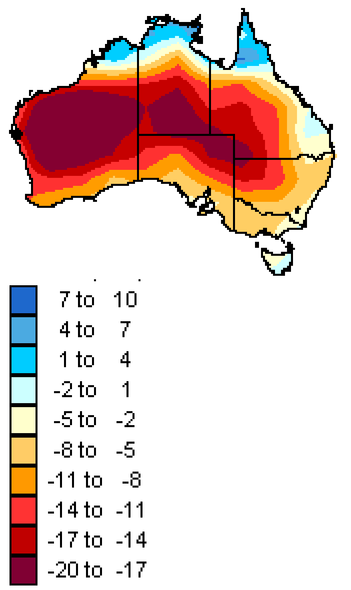
11.2 Global Climate Models Projections Used

To preserve the internal consistency of the model projections both temperature and rainfall monthly means were used from each model.

GISS-AOM

Host organisation NASA Goddard Institute for Space Studies (NASA/GISS)
Country of origin USA
Atmospheric and ocean model attributes
Atmosphere: 4° longitude, 3° latitude, 12 vertical layers
Ocean: 4° longitude, 3° latitude, up to 16 vertical layers

<table>
<tr><td>Annual rainfall pattern of change PDGW</td><td>Annual temperature pattern of change PDGW</td><td>Annual wind speed pattern of change PDGW</td></tr>
<tr><td>


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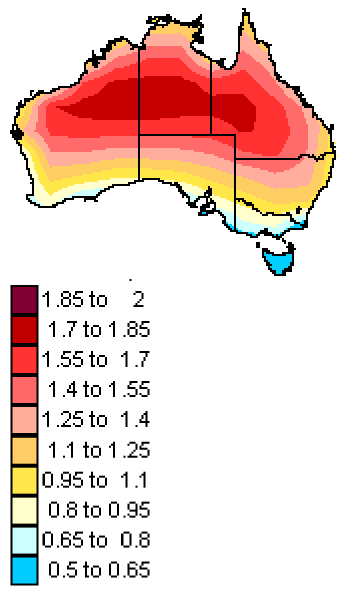

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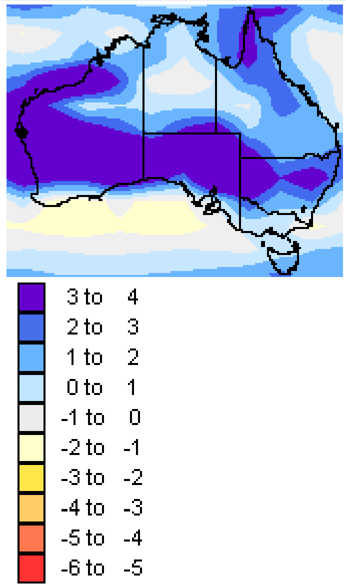
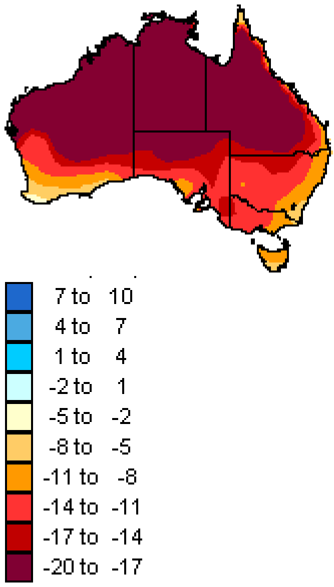
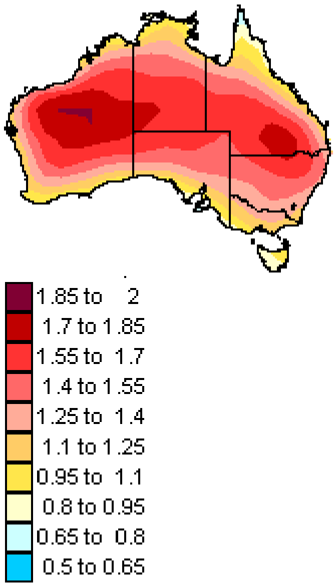
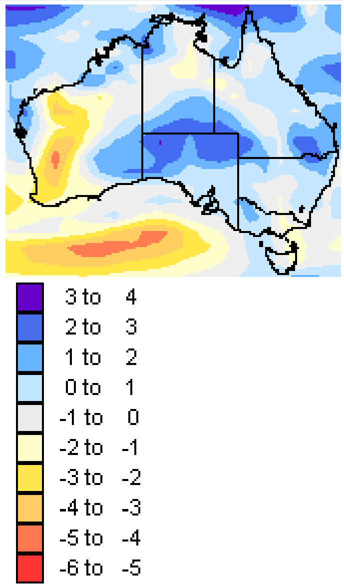


</td></tr>
<tr><td>Annual and seasonal averages show strong drying over all of mid-latitudes, with increases in the tropics. Tasmania shows summer decreases with increases in other seasons</td><td>Increases across all of Australia, greater inland, less along the southern coast of Australia, stronger in spring</td><td>Annual averages shows overall increases with winter showing zonal southern reductions and reductions in north Western Australia</td></tr>
</table>

Link to further information http://www-pcmdi.llnl.gov/ipcc/model_documentation/GISS-AOM.htm

CSIRO Mk3.5

Host organisation CSIRO
Country of origin Australia
Atmospheric and ocean model attributes
Atmosphere: 18 vertical levels, horizontal resolution 1.8° lat/long, approx 200 km between gridpoints
Ocean: 31 vertical levels, horizontal resolution matching the atmospheric model, but 100 km resolution in the tropics to enhance the simulation of the El Niño Southern Oscillation.

Annual rainfall pattern of change PDGW	Annual temperature pattern of change PDGW	Annual wind speed pattern of change PDGW
		
Annual-average decreases across all of Australia, except for increases along the east coast. Widespread decreases in all seasons, but increases in the south and east in summer and over NSW and southern Qld in autumn.	Increases across all of Australia, smaller increases along the southern coast of Australia	Generally moderate increases across most of Australia with decreases over the west of Western Australia.

http://www-pcmdi.llnl.gov/ipcc/model_documentation/CSIRO-Mk3.5.htm

MIROC-M

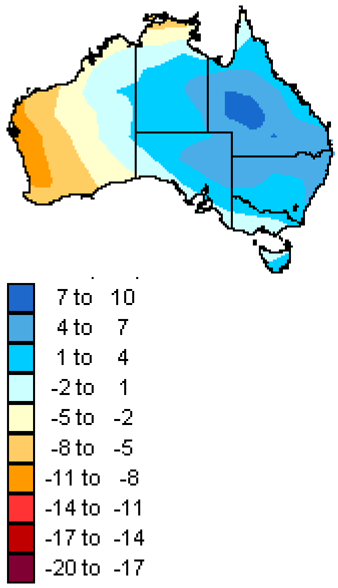
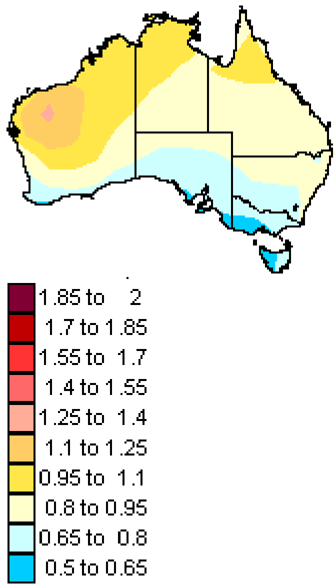
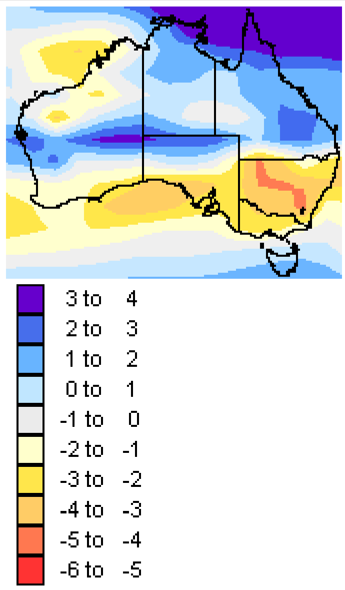
Host organisation Center for Climate System Research, University of Tokyo (CCR). National Institute for Environmental Studies.Frontier Research Center for Global Chance, Japan Agency for Marine-Earth Science and Technology (JAMSTEC)

Country of origin Japan

Atmospheric and ocean model attributes

Atmosphere: T42 20 vertical levels, 2.8°x2.8° horizontal resolution

Ocean: 43 vertical levels, 0.5°-1.4°x1.4° horizontal resolution

<table>
<tr><th>Annual rainfall pattern of change PDGW</th><th>Annual temperature pattern of change PDGW</th><th>Annual wind speed pattern of change PDGW</th></tr>
<tr><td>
</td><td>
</td><td>
</td></tr>
<tr><td>Annual averages show decreases to the west of Western Australia and increases elsewhere. Spring tends to be drier except in the south-east of Australia</td><td>Moderate increases across all of Australia,
smaller to the south and east.</td><td></td></tr>
</table>

Link to further information http://www-pcmdi.llnl.gov/ipcc/model_documentation/MIROC3.2_medres.htm

11.3 IPCC Scenarios

The SRES Marker Scenario A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system.

The A1B group is based on the A1 storyline and scenario family but describes a balance across all energy sources.
The A1FI group is based on the A1 storyline and scenario family but describes an alternative direction of technological change in the energy system by emphasizing fossil-fuel intensity.
The A1T group is also based on the A1 storyline and scenario family but emphasizes predominately non-fossil energy resources.

The SRES Marker Scenario A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing global population. Economic development is primarily regionally oriented and per capita economic growth and technological change is more fragmented and slower than in other storylines.
The SRES Marker Scenario B1 storyline and scenario family describes a convergent world with rapid change in economic structures, "dematerialization" and introduction of clean technologies. The emphasis is on global solutions to environmental and social sustainability, including concerted efforts for rapid technology development, dematerialization of the economy, and improving equity.
The SRES Marker Scenario B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with continuously increasing global population at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than

in the B1 and A1 storylines. While the scenario is also oriented toward environmental protection and social equity, it focuses on local and regional levels.

The carbon dioxide (CO_2) methane (CH_4) and sulfur dioxide (SO_2) emissions and concentrations associated with each of these scenarios are shown below along with radiative forcing and global warming. Scenarios for nitrous oxide, halocarbons, and ozone were also developed by the IPCC.

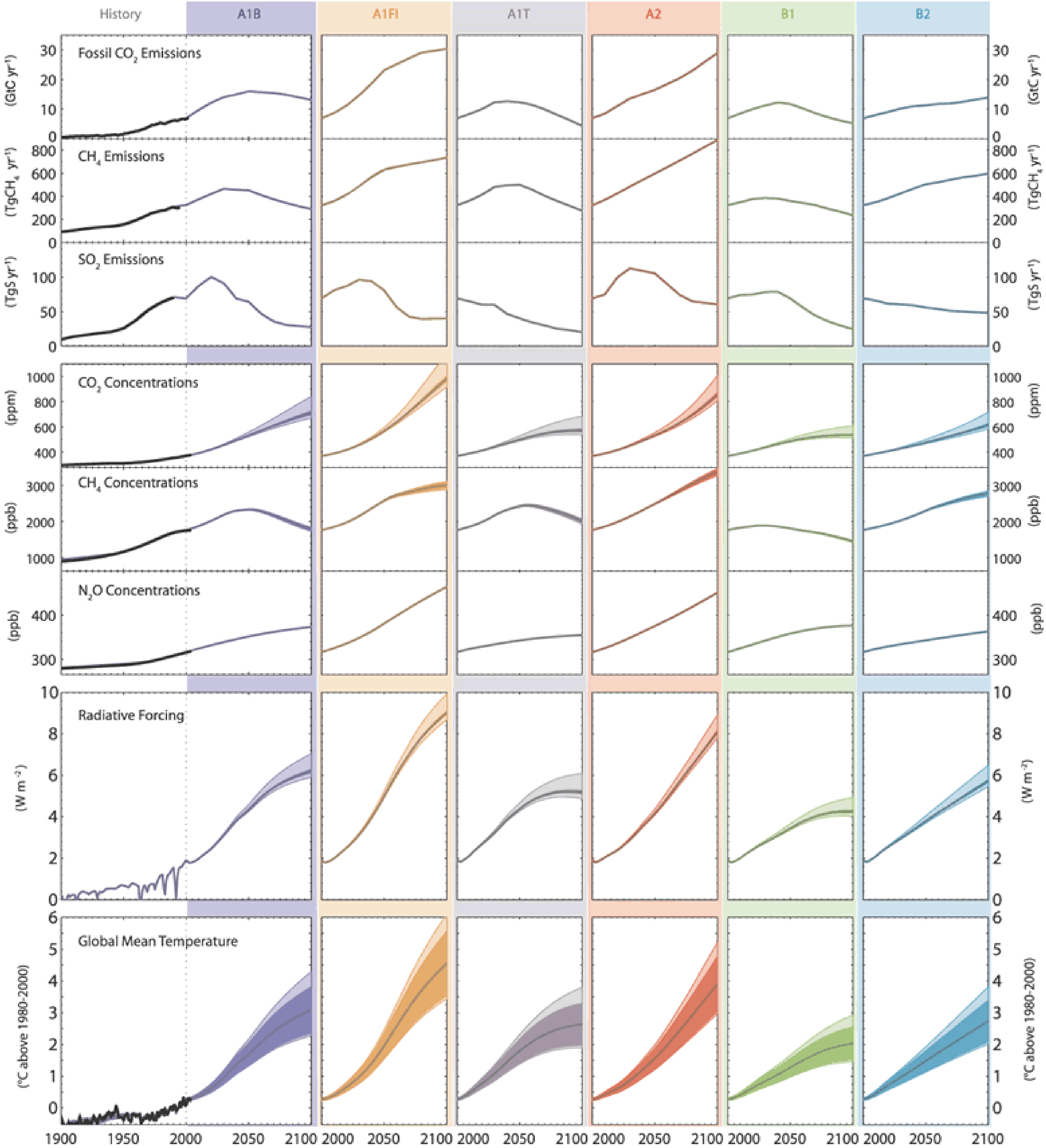


Figure: The carbon dioxide (CO2) methane (CH4) and sulfur dioxide (SO2)emissions and concentrations associated with six SRES scenarios (A1B, A1T A1FI, A2, B1, B2) along with radiative forcing and global warming.

The 450ppm stabilisation by 2100 scenario describes an emission reduction scenario that stabilises CO_2 concentrations at 450 parts per million (ppm) by the year 2100. This is shown in the yellow curves below. The 550ppm stabilisation by 2150 scenario describes an emission reduction scenario that stabilises CO_2 concentrations at 550 parts per million (ppm) by 2150. This is shown in the green curves below.

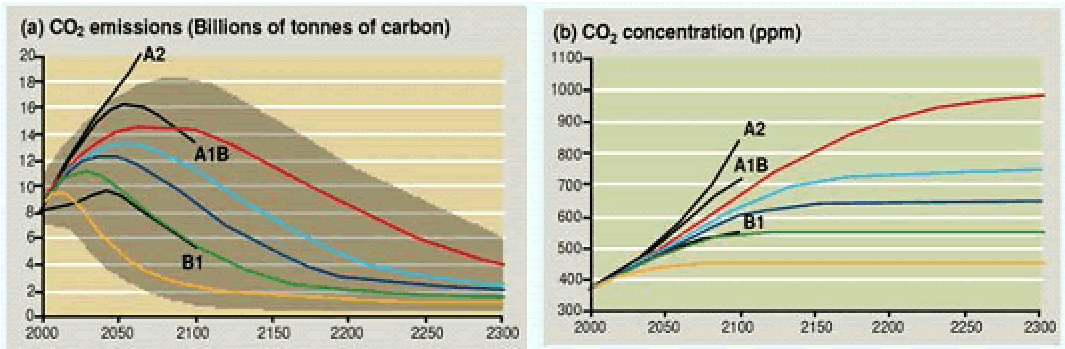


Figure: CO_2 emissions (left panel) and CO_2concentrations (right panel) for SRES emission scenarios A2, A1B, B1 (black lines), emission reduction scenario that stabilises CO_2 concentrations at 450ppm by 2100 (yellow) and emission reduction scenario that stabilises CO_2concentrations at 550ppm by 2150 (green). Also shown are stablisation scenarios for 650 ppm by 2200 (blue), 750 ppm by 2250 (cyan) and 1000 ppm by 2300 (red).

11.4 Climate change projects in horticulture – full listing

The following tables show all current and recent HAL projects related to climate change. The funding allocation to these projects is shown in the investment column and does not include in-kind contributions from institutions.

Expenditure summary:

Project area	Investment
Vegetable	$5,104,347
Amenity	$6,411,376
Cross-horticulture	$4,180,034
Perennial	$4,184,860
Total	$19,880,617

Vegetable Projects

Org	Project number	Project title	Start Date	Finish date	Investment – cash	Lead agency	Project leader
DAFF	GMS-0774	Carbon and sustainability – A demonstration of how they relate and how they can be managed within the Australian Vegetable Industry.	1/06/10	30/06/12	1,687,892	Horticulture Australia Limited	Peter Melville
DAFF_Qld		Energy Efficiency in Australia Glasshouse Horticulture	15/01/10	31/05/13	205,000	NSW DPI	Jeremy Badgery-Parker
DPIPWE/TIA	100380	Development and demonstration of controlled traffic farming techniques for production of potatoes and other veg	2009	2014	396,562	TIA	J McPhee
DPIPWE/TIA	39470	Precision Agriculture Irrigation Applied to Diff Veg Crops	2008	2012	398,733	TIA	S Lambert
DPIPWE/TIA	101623	On farm demonstrations of 209controlled traffic farming for vegetables	2010	2013	306,643	TIA	J McPhee
HAL	VG09138	Quantifying the effects of no till vegetable farming and organic mulch on greenhouse gas emissions and soil carbon	16/10/09	31/03/12	411,000	Applied Horticultural Research P/L	Gordon Rogers
HAL	VG09019	Economic and carbon emissions model for controlled traffic farming in vegetables	1/07/09	30/06/12	210,576	TIA	John McPhee
HAL	VG08029	Design and demonstration of precision agriculture irrigation applied to different vegetable crops	1/12/08	2/07/12	398,733	Utas	Susan Lambert

HAL	VG10080	On-farm demonstration of controlled traffic farming for vegetables	15/12/10	30/06/13	306,644	TIA	John McPhee
HAL	HG10025	Novel, Sustainable and Profitable Horticultural Management Systems: Soil Amendments and Carbon Sequestration	15/11/10	30/05/14	302,193	UQ	Jitka Kochanek
HAL	VG09124	Increasing energy efficiency and assessing an alternate energy option for Australian Protected Cropping	15/01/10	31/10/13	480,372	NSW DPI	Jeremy Badgery-Parker

Amenity Horticulture

Org	Project number	Project title	Start Date	Finish date	Investment – cash	Lead agency	Project leader
HAL	TU11012	Effectively utilising water allocations for managing turfgrass in open spaces	10/11/11	1/10/15	526,957	Uni of WA	Louise Barton
HAL	NY11007	Identification and Evaluation of Water conservation products and technologies for the Australian urban outdoor market	30/09/11	29/05/12	154,000	Smart Approved Watermark	Julian Gray
HAL	NY11013	Greening City - Mitigate Heat Stress with Urban Vegetation	13/07/11	30/06/13	276,000	CSIRO	Dong Chen
HAL	TU08007	Warm season grass evaluations for turf in cold climates	26/06/09	26/06/12	44,851	University of Sydney	Peter Martin
HAL	TU09001	Adaptation of warm-season turf grasses for tropical Australia	1/06/10	31/05/13	305,221	DEEDI	Matthew Roche
HAL	NY11002	Understanding the carbon and pollution mitigation potential of Australia's urban forest	31/08/11	28/08/13	139,994	Macquarie University	Marco Amati

Horticulture Cross Industry

Org	Project number	Project title	Start Date	Finish date	Investment – cash	Lead agency	Project leader
DAFF_Qld	QPI005130	Critical temperature thresholds and climate change in horticulture	1/01/09	31/01/2011 (extension process underway)	207,000	DAFF Qld	Peter Deuter
DPI Vic	102313	Regional CC impact on horticulture (08444)	1/07/08	30/06/12	400,000	DPIV	Victor Sposito
DPI Vic	102376	Water and Climate Change in Horticulture Industries	1/07/08	30/06/12	599,000	DPIV	Pam Strange
DPI Vic	102603	Delivering a route to market for horticulture climate change research	1/07/08	30/06/12	520,000	DPIV	Pam Strange
DPI Vic	103287	Shaping the Future of Sunraysia's Irrigation	1/07/09	30/06/12	575,000		Sue McConnell
DPIPWE/TIA	100947	Developing Climate Change Adaptation Research in Tasmania	2010	2013	150,000	TIA	C Mohammed
DPIPWE/TIA	39116	Developing Climate Change Adaptation Research in Tasmania	2009	2012	75,000	TIA	D McNeil
DPIPWE/TIA	101082	Quantifying Relative Contribution of Physiological Traits	2010	2014	502,024	TIA	S Shabala
DPIPWE/TIA	39126	Soil organic carbon balances in Tas agriculture systems	2009	2012	600,000	TIA	R Doyle
DPIPWE/TIA	101791	Wealth for Water Program	2011	2012	305,500	TIA	L Sparrow

HAL	AH09014	Across-industry climate research, development and extension (RD&E) activities	13/04/10	31/01/12	75,126	HAL	Peter Melville
HAL	AH11006	Carbon Amelioration in Horticulture	1/12/11	31/08/12	78,010	NSW DPI	Justine Cox
HAL	AH11019	The impacts of the proposed carbon price mechanism on Australian horticulture	29/11/11	31/05/12	49,874	Growcom	David Putland
HAL	AH11020	Opportunities for Australian horticulture in the Carbon Farming Initiative	29/11/11	25/05/12	43,500	Growcom	David Putland

Perennial Horticultural crops

Org	Project number	Project title	Start Date	Finish date	Investment – cash	Lead agency	Project leader
DAFF_Qld	AVO9003	Climate Change and Climate Policy Implications for the Australian Avocado industry	1/12/09	31/12/11	24,000	Growcom	David Putland
DPI NSW	102186	Flesh browning for Cripps pink apples	1/08/08	28/06/13	108,500	NSW DPI	John Golding
DPI Vic	103037	Modelling climate change impacts on perennial horticulture (08638)	1/07/09	30/06/13	965,001	DPIV	Kristen Pitt
DPI Vic	102303	Managing disruption to water supply in perennial horticulture in a changing climate (08467).	1/07/08	30/09/12	1,889,378	DPIV	Karl Sommer
HAL	AL08009	Optimising water use of Australian almond production through deficit irrigation strategies	31/12/08	30/09/12	295,939	Vic DPI	Karl Sommer
HAL	CT08014	Citrus Drought Survival and Recovery Trial	1/09/08	31/12/13	456,710	SARDI	Mark Skewes
HAL	MC10005	Wild about macadamias - conserving a national icon	1/08/10	31/08/13	435,332	Australian Macadamia Society Limited	Maria Matthes
HAL	CY11010	Cherry cultivar selection: chill hours and climate change	1/07/11	1/03/12	10,000	Biometry	Charlotte Brunt

11.5 Appendix: Growing regions by crop and harvest time of year for the Australian vegetable industry (ABS with modifications)

State	Region	Area (ha)	Crops	Harvest times	
				Start	End
NT					
	Darwin	300	vegetables general	January	December
	Katherine	800	watermelons	April	May
			rockmelons		
Total NT		1100			
Tasmania					
	Cambridge, Hobart	1000	baby leaf	January	December
			lettuce and brassicas	September	June
	NW Devonport, Smithton	6400	potatoes	November	May
			onions	January	May
			lettuce	October	June
			celery	January	December
			brassicas	January	December
			beans	December	April
			carrots	January	June
	NW Scottsdale	4400	potatoes	January	June
			onions	February	May
			carrots	January	June
	Cressy (Midlands)	500	broccoli	January	May
			onions	February	April

Total Tasmania	12300			
Western Australia				
Perth metropolitan	3400	lettuce	January	December
		brassicas	January	December
		baby leaf	January	December
		Asian vegetables	January	December
		carrots	January	December
		potatoes	January	December
		tomatoes	December	May
Manjimup, Pemberton	3400	lettuce	November	June
		baby leaf	November	June
		brassicas	January	December
		potatoes	January	December
Carnarvon	1400	tomatoes	May	December
		cucurbits	May	December
		sweet corn	May	December
		beans	May	December
Kununurra, Broome	700	rockmelons	May	November
		watermelons	May	November
		pumpkin	May	November
		sweet corn	May	November
		beans	May	November
Total Western Australia	8900			

South Australia

	Riverland, Murray Bridge	6900	Onions	January	April
			Potatoes	January	December
			Carrots	January	December
	Virginia, Adelaide Plains	2000	lettuce	January	December
			brassicas	January	December
			carrots	January	December
			tomatoes (glasshouse)	January	December
			onions	February	April
			cucumber (glasshouse)	January	December
	Adelaide Hills	700	leeks	December	April
			lettuce	December	April
			celery	December	April
			brassicas	December	April
	Mt Gambier, Pinnaroo	4300	onions	December	April
			potatoes	November	June
Total South Australia		13900			

Victoria

Werribee	5500	lettuce	October	June
		brassicas	October	June
		cauliflower	July	September
Melbourne sandbelt	6,500	lettuce	January	December
		celery	January	December
		parsnips	January	December
		baby leaf	January	December
		salad onions	January	December
		potatoes	January	May
		Asparagus	September	November
Thorpdale, West Gippsland	5000	potatoes	January	May
East Gippsland (Sale, Maffra,	2600	lettuce	January	December
		baby leaf	January	December
		brassicas	January	December
		sweet corn	January	May
		beans	January	May
		carrots	January	December
Goulburn Valley, Upper Murray,	4500	Tomatoes (Fresh market)	January	May
		Tomatoes (Processing)	February	April
Mildura, Robinvale, Swan Hill	2000	carrots	January	December
		lettuce	May	December
		baby leaf	May	December

		brassicas	May	December
		rockmelons	December	April
		watermelons	December	April
		potatoes	November	December
		potatoes	April	May
		capsicums (glasshouse)	November	January
Total Victoria	26100			

New South Wales

Sydney basin, Mangrove	3500	leafy vegetables	January	December
		Asian bunching vegetables	January	December
		lettuce	January	December
		bunching onions	January	December
		Lebanese cucumbers (glasshouse)	January	December
		Tomatoes (glasshouse)	January	December
Central tablelands (Bathurst,	1210	brassicas	December	May
		lettuce	December	May
		sweet corn	January	April
Lachlan valley (Cowra,	2130	brassicas	April	December
		lettuce	April	December
		watermelons	January	April
		sweet corn	January	May
		beetroot	April	November
MIA, Hillston, Hay	4000	rockmelons	January	April
		watermelons	January	April
		onions	November	January
		tomatoes (processing)	January	March
		sweet corn	December	January
		beetroot (Hillston)	April	November
Finley, Berrigan	660	potatoes	November	December
		potatoes	April	June

Murray - NSW side (Barum,	440	potatoes	November	December
		potatoes	April	June
		onions	November	December
		onions	April	June
Northern Rivers (North coast)	1123	cucurbits	January	December
		tomatoes	January	December
		sweet potatoes	January	December
Total NSW	13063			

Queensland

Bowen, Gumlu, Ayr	6330	tomatoes	May	November
		capsicums	May	November
		sweet corn	May	November
		beans	May	November
		rockmelons	May	November
Bundaberg, Gympie	7100	tomatoes	April	December
		capsicums	April	December
		zucchini	April	December
		squash	April	December
		baby leaf (Gin Gin)	April	December
		watermelon	April	December
		sweet potatoes	April	December
Lockyer valley	11800	brassicas	May	October
		lettuce	May	October
		baby leaf	May	October
		celery	May	October
		carrots	May	October
		tomatoes	April	May
		tomatoes	October	December
		potatoes	April	May
		potatoes	October	December
		sweet corn	April	May
		sweet corn	October	December
		beans	April	May
		beans	October	December

		onions	September	November
Fassifern valley (Kalbar)		carrots	June	December
		onions	November	January
Stanthorpe		lettuce	October	May
		celery	October	May
		baby leaf	October	May
		brassicas	October	May
Toowoomba, Eastern Darling		lettuce	October	November
		onions	December	February
Chinchilla	2700	watermelons	January	April
		rockmelons	January	April
Fizroy (Rockhampton)	1000	sweet potatoes	January	December
		potatoes	August	October
Emerald	500	melons		
Wet Tropics (Atherton	2300	Potatoes	July	November
		lettuce	July	November
St George	2400	rockmelons	January	April
		watermelons	January	April
		onions	November	February
Total Queensland	34130			
Total area	109493			

11.6 Appendix What would 4 degrees of global warming look like: figures

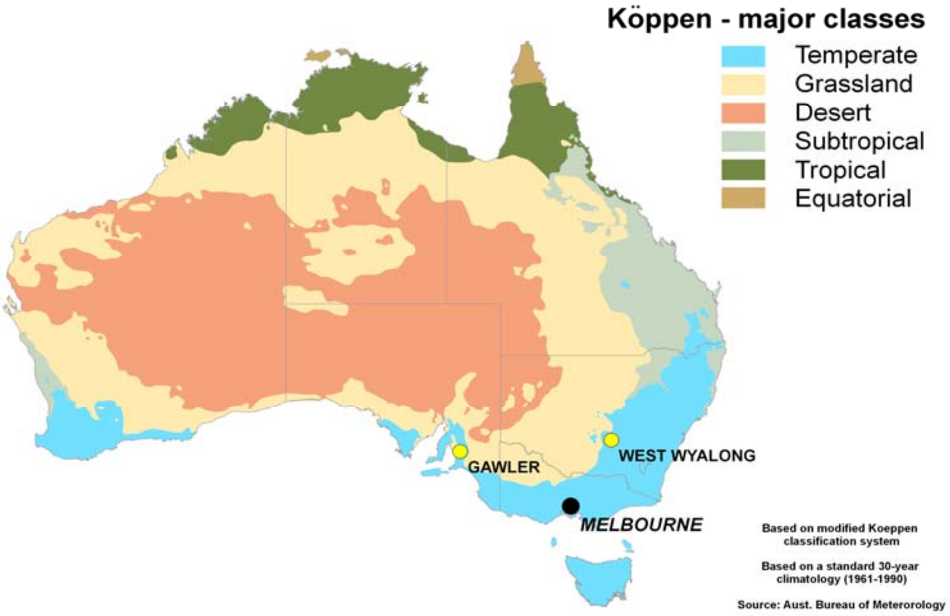


Figure 59. Melbourne becomes like West Wyalong and Gawler

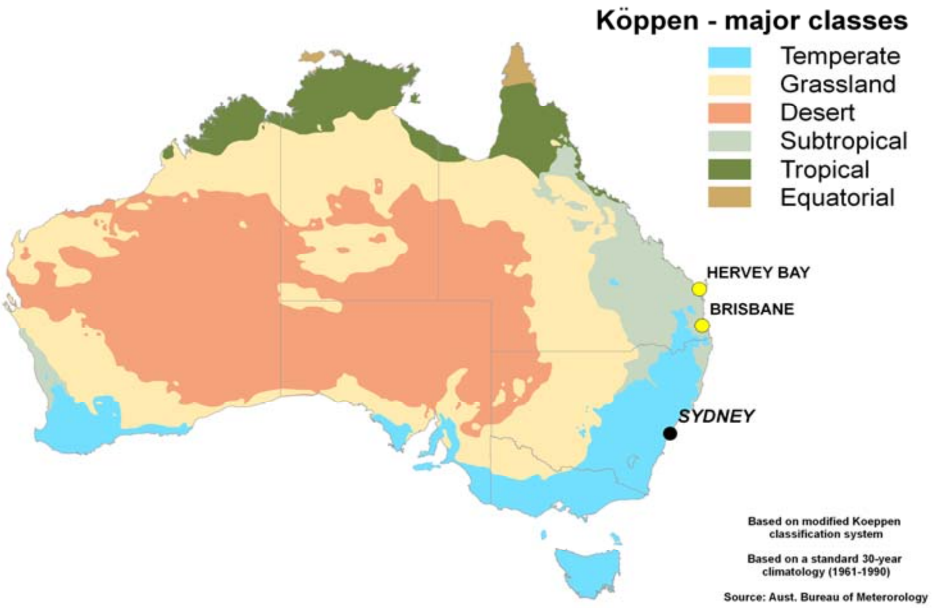


Figure 60. Sydney becomes like Brisbane and Hervey Bay

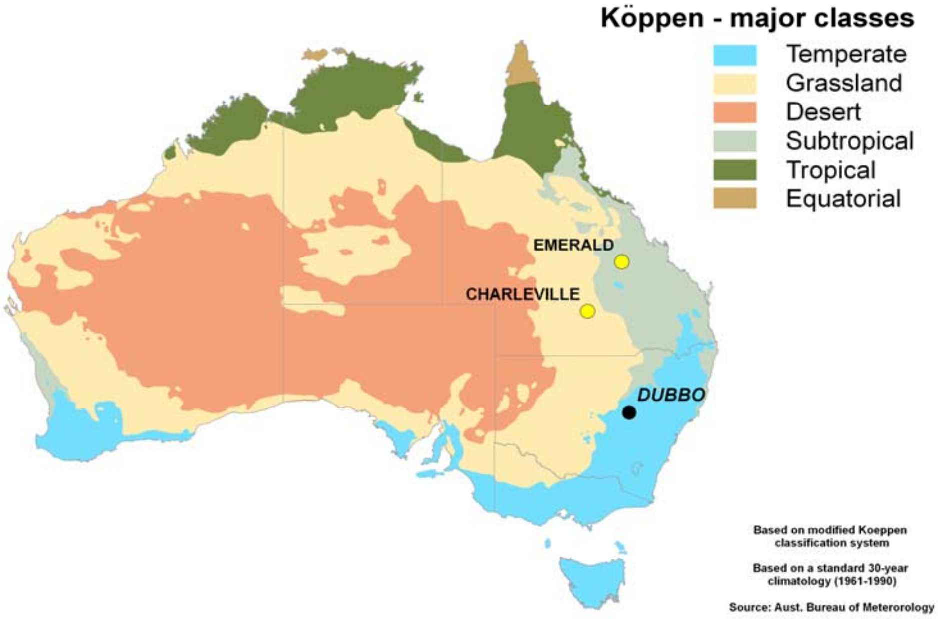


Figure 61. Dubbo becomes like Charleville and Emerald

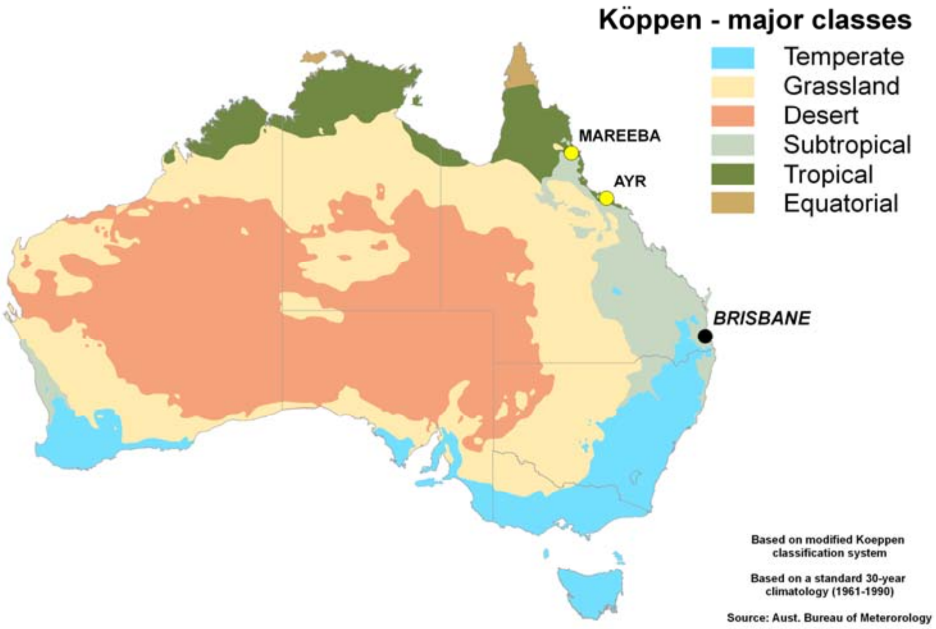


Figure 62. Brisbane becomes like Ayr and Mareeba

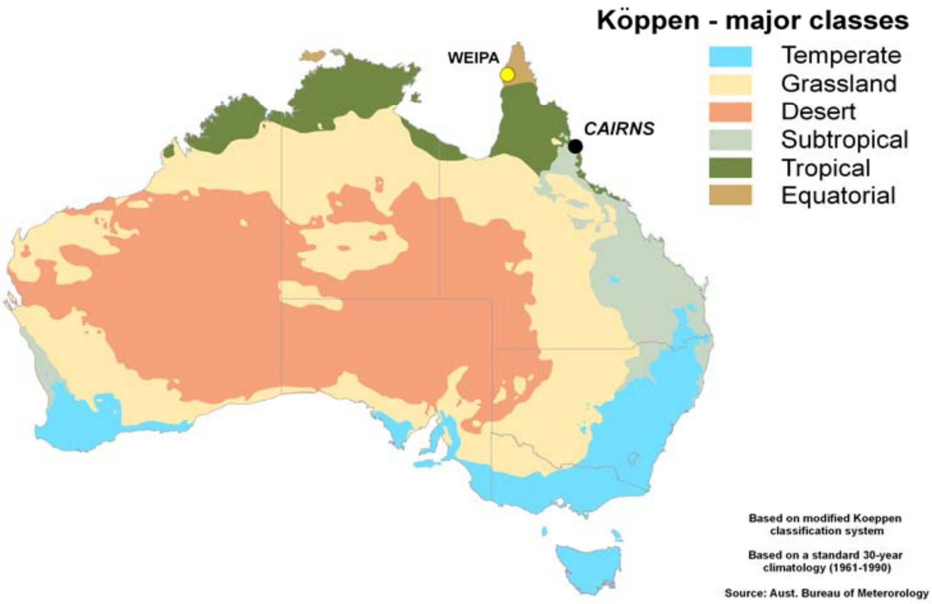


Figure 63. Cairns becomes like Weipa

11.7 Appendix – Drivers of climate variability

Below, the regional impacts of these circulation features are summarised, together with a short description of how they affect Australia. This section draws on information from the Managing Climate Variability program and the Bureau of Metrology. Maps of the regions affected are also provided[150].

11.7.1 El Niño and La Niña

El Niño Southern Oscillation (ENSO) is the term used to describe the oscillation between the El Niño phase and the La Niña, or opposite, phase. The Southern Oscillation Index, or SOI, gives an indication of the development and intensity of El Niño or La Niña events in the Pacific Ocean.

El Niño

El Niño is normally associated with lower than average winter/spring rainfall over much of eastern Australia as indicated by the blue areas on the map. The greatest impact normally occurs during the winter/spring period. This typically occurs every three to eight years. El Niño events tend to begin in autumn, mature during winter and spring, and then begin to decay in summer, with the event generally ending in the autumn of the following year.

El Niño is the negative phase of the El Niño Southern Oscillation. It is associated with warmer than average sea surface temperatures in the central and eastern tropical Pacific.

La Niña

La Niña is normally associated with higher than average winter, spring and early summer rainfall over much of Australia as indicated by the blue areas on the map. Events generally end in the autumn. La Niña events normally last for about a year; however they can be shorter, or much longer.

La Niña is the positive phase of the El Niño Southern Oscillation. It is associated with cooler than average sea surface temperatures (SSTs) in the central and eastern tropical Pacific

150 Bureau of Meterology, Commonwealth of Australia. http://www.bom.gov.au/watl, accessed 19/3/2013.

Ocean. La Niña events tend to begin in autumn, mature during winter, spring and early summer, and then begin to decay in late summer.

11.7.2 Sub-tropical Ridge

The sub-tropical ridge runs across a belt of high pressure that encircles the globe in the middle latitudes. It is part of the global circulation of the atmosphere. The position of the sub-tropical ridge plays an important part in the way the weather in Australia varies from season to season as indicated by the blue areas on the map.

During the warmer part of the year in southern Australia, the ridge is located to the south of the continent. During this time, the high pressure systems along the ridge tend to suppress (cold) frontal activity. This means that any cold fronts that do penetrate the ridge generally tend to be weaker and the weather (such as rainfall, temperature and wind) associated with these systems is generally less intense than during the winter time (when the ridge is further northward).

As southern Australia cools and winter approaches, the sub-tropical ridge moves northward over central Australia. As the ridge moves over inland Australia, cold fronts associated with low pressure systems begin to extend further into southern Australia. These wintertime cold fronts are associated with colder south-westerly winds and showery conditions.

11.7.3 Southern Annular Mode

The Southern Annular Mode, or SAM, can affect rainfall in southern Australia as indicated by the blue areas on the map. The SAM refers to the north/south movement of the strong westerly winds that dominate the middle to higher latitudes of the Southern Hemisphere. The belt of strong westerly winds in the Southern Hemisphere is also associated with the storm systems and cold fronts that move from west to east.

During a "positive" SAM event, the belt of strong westerly winds contracts towards the South Pole. This results in weaker than normal westerly winds and higher pressure over southern Australia. Conversely, a "negative" SAM event reflects an equator-ward expansion of the belt of strong westerly winds. This shift in the westerly winds results in more storm systems and lower pressure over southern Australia.

The impact that the SAM has on rainfall varies greatly depending on season and region. The SAM also has an impact on temperatures. In general, in areas where rainfall is increased, temperature is decreased whilst where rainfall is decreased, temperature is increased.

The contribution that the SAM makes to the climate variability in Australia and the apparent positive trend in the SAM are relatively recent discoveries and as such are still active areas of research.

11.7.4 Madden-Julian Oscillation

The Madden-Julian Oscillation (MJO) is associated with weekly to monthly periods of enhanced and suppressed rainfall over parts of Australia as indicated by the blue areas on the map.

The Madden-Julian Oscillation (MJO) is a global-scale feature of the tropical atmosphere.

The MJO is the major fluctuation in tropical weather on weekly to monthly timescales. The MJO can be characterized as an eastward moving "pulse" of cloud and rainfall near the equator that typically recurs every 30 to 60 days. However, the signal of the MJO in the tropical atmosphere is not always present.

MJO effects are most evident over the Indian Ocean and western equatorial Pacific. It influences the timing, development and strength of the major global monsoon patterns, including the Indian and Australian monsoons.

The MJO has its greatest effect on the tropical areas of Australia during summer. It may have some effect on parts of southern Australia, however this impact appears small when compared to the effect on northern regions, and remains the subject of research.

The MJO can have an effect on the timing and intensity of "active" monsoon periods in northern Australia. This can lead to enhanced rainfall - in both the intensity of the rainfall and the duration of the rainfall.

11.7.5 Blocking Highs

Blocking highs disrupt the flow of low pressure systems across southern Australia as indicated by the blue areas on the map. Blocking highs are strong high pressure systems which have formed further south than usual and remain near stationary for an extended period of time. These highs essentially "block" the west to east progression of weather systems across southern Australia.

Blocking highs are often, although not always, associated with a cut-off low which may form to the north of the blocking high, the two systems creating a blocking pattern. As frontal systems approach the blocking high, they slow down, weaken and tend to slip to the south of the high pressure system.

Blocking highs have a wide range of impacts depending on their location and strength. A blocking high can produce a hot spell, a cold spell, dry conditions or wet conditions depending on it's location and the systems around it. Blocking highs can also be associated with greater probabilities of fog and frost occurrence.

Areas under the influence of a blocking high could experience dry and stable conditions, however areas to the west of the high could experience wet conditions as the frontal systems approaching become very slow moving. If the high was associated with a cut-off low forming a blocking pattern, then affected areas could experience sustained heavy rainfall. Regions on the northwestern side of the blocking high may experience warmer than average conditions under a north-westerly wind flow, whilst areas on the southeast of the high could experience cooler than average conditions as cold air is brought up from the far south.

11.7.6 Cut-off Lows

Cut-off lows bring enhanced rainfall to parts of southern Australia as indicated by the blue areas on the map. Cut-off lows are low pressure systems which have broken away, or are cut-off, from the main belt of low pressure which lies to the south of Australia. They can be at any level in the atmosphere, and therefore may not show on the surface charts.

A cut-off low may develop when a low pressure system forms on an active cold front. Alternatively, they may form in an unstable easterly flow on the northern flank of a slow-moving or blocking high. This dual system is sometimes referred to as a blocking pair.

Cut-off lows are associated with sustained, and often heavy, rainfall and can produce strong and gusty winds and high seas.

11.7.7 East Coast Lows

East coast lows bring heavy rainfall and strong and gusty winds to parts of southeastern Australia as indicated by the blue areas on the map. East coast lows are intense low-pressure systems which occur on average several times each year off the eastern coast of Australia, in particular southern Queensland, New South Wales (NSW) and eastern Victoria.

East coast lows will often rapidly intensify overnight making them one of the more dangerous weather systems to affect the southeast Australian coast.

East coast lows are generally associated with strong and gusty winds, sustained heavy rainfall and high seas. They can cause widespread damage over a very short period of time. East coast lows can form at any time of year, however they are most common during autumn and winter with a maximum frequency in June.

11.7.8 Easterly Trough

Easterly, or inland, troughs bring rainfall to central and inland parts of eastern Australia as indicated by the blue areas on the map.

Easterly troughs are a dominant feature of the synoptic pattern over Australia during the summer months. The trough is located on the lee side (inland side) of the Great Dividing Range, forming a boundary between the moist air near the coast and dry air inland. It extends through central Queensland and central New South Wales, sometimes extending right down into northern Victoria. It is partly formed by the intense heating of the land during the summer months, but the topography of the region also plays a role.

While an easterly trough forms to the west of The Great Dividing Range, a ridge of higher pressure will also form along the coast. This is particularly evident when a high pressure system is located in the Tasman Sea, with southeaserly winds along the Queensland coast.

As the temperature rises during the day, the trough deepens and moves towards the coast, causing showers and thunderstorms to form in the unstable air. The trough will also interact with any low pressure troughs or cold fronts moving through southern Australia, enhancing the impact they may have on the region. The easterly trough is a major contributor to rainfall in eastern Australia. Rainfall can be particularly heavy when the trough interacts with other features, such an upper level trough approaching from the west, or when on-shore flow is north-easterly and hence the ridge of higher pressure to the windward side of the Great Dividing is absent.

11.7.9 Frontal Systems

Frontal systems bring rainfall to southern Australia as indicated by the blue areas on the map.

Australia can be affected by both warm fronts and cold fronts, however cold fronts are more common and have a greater impact on the Australian region.

A cold front is formed when cold dense air advances equatorwards, causing warm air to be forced aloft over its sloping surface. A warm front is formed when warm air of lower density moves polewards, sliding over the sloping surface formed by a colder air mass.

Frontal systems bring rainfall to southern Australia. These frontal systems vary in their intensity and speed, and the more intense (stronger) systems are generally associated with heavier rainfall. If frontal systems are slower moving, then rainfall may occur for extended periods and may be heavy at times.

11.7.10 Indian Ocean

Sea Surface Temperatures in the Indian Ocean can influence the rainfall patterns over much of Australia as indicated by the blue areas on the map.

Sea Surface Temperatures (SST's) in the Indian Ocean have a profound impact on the rainfall patterns over much of Australia. In general, warmer than average Indian Ocean SST's near Australia may enhance Australian rainfall whilst cooler than average SST's can result in reduced rainfall.

The most commonly referred to Indian Ocean influence upon Australian climate is called the Indian Ocean Dipole (IOD). The Indian Ocean Dipole is a major contributor to the variability of rainfall over Australia. When the dipole is in a positive phase, SST's around Indonesia are cooler than average whilst those in the western Indian Ocean are warmer than average. There is an increase in the easterly winds across the Indian Ocean in association with this SST pattern, while convection in areas near Australia reduces. This results in suppressed rainfall over the Australian region. Conversely, during a negative phase, there are warmer than average SST's near Indonesia and cooler than average SST's in the western Indian Ocean, resulting in more westerly winds across the Indian Ocean, greater convection near Australia, and enhanced rainfall in the Australian region.

IOD events can be related to ENSO events. Positive IOD events sometimes occur during El Niño events, usually resulting in less rainfall over affected regions. Conversely, negative IOD events sometimes occur during La Niña events, usually resulting in increased rainfall over affected regions.

Generally speaking, warmer than average SST's in the Indian Ocean near Indonesia will result in enhanced rainfall over Australia, and cooler than average SST's in this region may mean reduced Australian rainfall. However, the effect the SST's in the Indian Ocean have on Australia varies greatly by region and is still an active area of research.

11.7.11 Upper Level Trough

Upper level troughs can bring enhanced rainfall to Australia as indicated by the blue areas on the map.

An upper level trough is a trough of low pressure which has formed in the upper levels of the atmosphere, and hence cannot be seen on surface level charts. Upper level troughs can result in the formation of a cloudbands, which will often result in widespread rainfall near and to the east of the trough. Upper level troughs can also aid in the development of surface level features, such as frontal systems, thereby enhancing their effect. The presence of an upper level trough in a favourable position may result in the development of a cut-off low, which in turn will enhance rainfall over the affected region.

11.7.12 West Coast Trough

The west coast trough affects temperatures, winds and thunderstorm development near the west coast of Australia during the warmer months of the year as indicated by the blue areas on the map.

The west coast trough is a semi-permanent feature of the surface pressure pattern near the west coast of Australia during the warmer months, and is the dominant influence on west coast weather conditions at this time. The trough is a zone of low pressure that develops at the boundary between warm continental easterly winds driven by the sub-tropical ridge to the south, and cooler maritime air from the Indian Ocean.

The trough typically extends northwards to meet a heat low (a low pressure system formed by hot rising air) in the northwest Australian Pilbara region and can move westward off the coast, or inland depending upon the variation of the prevailing synoptic flow. A typical sequence is for the trough to deepen near the west coast over a period of days as winds to the east of the trough tend warmer north-easterly under the influence of a strong high pressure system in the sub-tropical ridge, in or south of the Great Australian Bight. With the approach of a cold front to the southwest of Australia, the trough will generally move eastward over inland Australia. The sequence of trough development begins again when a high following the front moves south of Australia and easterly winds again become established near the west coast.

Depending on the stage of development of the trough, areas to the east can experience hot days with temperatures above 40°C, and the possibility of thunderstorms given sufficient atmospheric moisture, whilst to the west of the trough, milder conditions with sea breezes generally prevail.

The position of the trough is dependent upon the prevailing background surface pressure pattern, however it can display variations during the day, remaining offshore during the morning, but moving inland during the afternoon to bring cooling sea breezes to the west coast. It is common for strong sea breezes to develop during the day west of the trough along northern parts of the west coast.

West coast troughs are commonly associated with fine weather, however as the trough deepens, thunderstorms can form east of the trough if sufficient moisture is available, whilst on some occasions, the trough can interact with upper level troughs moving over the west coast to produce a significant rain event. These events are rare, but can be responsible for heavy rainfall.