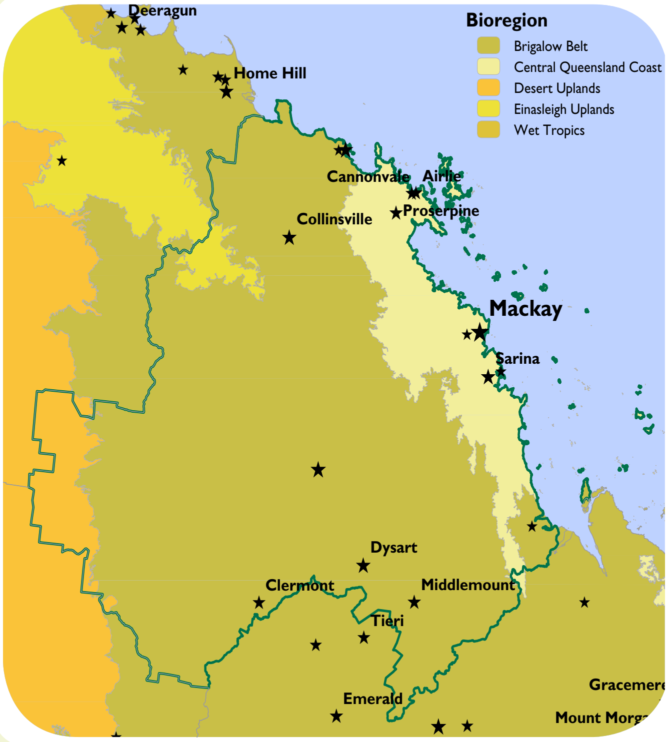
Courtesy of Tourism Queensland

Impacts and adaptation strategies for a variable and changing climate in the **Whitsunday, Hinterland and Mackay Region**



This summary describes the likely impacts of a variable and changing climate on the major primary industries of the Whitsunday, Hinterland and Mackay (WHM) region including grazing, horticulture, sugar, fisheries and aquaculture, and the potential adaptation strategies which can be implemented to minimise risks.

Courtesy of Tourism Queensland

Regional Profile

The Whitsunday Hinterland Mackay (WHM) region is located on the central Queensland coastline and is a major contributor to Queensland's economy through its major industries of mining, agriculture and tourism. The region's coastline is characterised by sandy beaches, rocky headlands, coastal wetlands and extensive mangrove communities. In the inland area, the landscape is made up of open savannah woodland and scattered patches of Brigalow forest where extensive agricultural activity is taking place.

The region has a typical tropical climate with hot and wet weather in summer with average historical annual rainfall ranging from 661 mm at Clermont to 1681 mm at Mackay (1890-2015). Temperatures range from an average annual minimum of 16.8°C to an average annual maximum of 27.5°C. Tropical cyclones and intensive thunderstorms also occur from late spring through to early autumn. The region is also susceptible to the natural hazards of flood, cyclone, drought and bushfire.

Major Primary Industries

The WHM region provides a wide range of diverse habitats and ecosystems to support biodiversity. At the same time, about two-thirds of the region's total area is used for rural production. The beef cattle industry is the largest individual user of land, which lies predominately in the western parts of the region. Cattle numbers can change significantly from year to year, mainly influenced by seasonal climate conditions and export prices. Dryland farming of grain and sunflower occurs in the Central Highlands. The region has a large sugarcane growing area, mainly located in the high rainfall, or in irrigated areas such as Sarina, Mackay and Proserpine districts. There is a horticulture industry around Bowen which produces fruit and vegetables (WRC 2012). An aquaculture industry is emerging including the land-based farming of prawns, red-claw and barramundi. The Great Barrier Reef and islands are home to a vast number of temperate and tropical species of reef and pelagic fish that support a commercial fishing industry. The gross value of production (GVP) in 2010-11 of agricultural commodities in the region was $443 M or 3.7% of the state total GVP for agricultural commodities ($11.9 B, ABS 2016a).

Courtesy of Tourism Queensland

Climate Trends and Projections

Historical changes in the key climate variables relevant to agricultural production including temperature, evaporation, rainfall, sea surface temperature and duration of warm periods are summarised in Table 1. Table 2 provides information on the historical means for the key variables and the projected changes for 2030.

Table 1: Historical Climate Trends (Interpreted and summarised from BOM 2016)

Variable	*Trend Since* (year)	*Change per decade*		
		Annual	Summer	Winter
Maximum Temperature (°C)	1950	+0.10 to +0.20	+0.10 (west) to +0.30 (east)	+0.05 to +0.20 (south)
Minimum Temperature (°C)	1950	+0.10 to+0.30	+0.10 (east) to +0.30 (west)	+0.10 (north) to +0.40 (south)
Mean Temperature (°C)	1950	+0.10 to +0.30	+0.20	+0.10 (north) to +0.30 (south)
Pan Evaporation (mm)	1970	-5 (north) to +10 (south)	-2.5 (north) to +2.5 (south)	-2.5 to +2.5 (west)
Rainfall (mm)	1950	-60 (east) to 20 (west)	-40 (east) to 50 (west)	-5 (west) to +5 (east)
Sea Surface Temperature (°C)	1950	+0.08 to +0.12	+0.08 to +0.12	+0.08 to +0.12
Cold Spell Duration	1970	-1.5 days		

NSC – No significant change | Unknown Number of Hot Days and Growing Season Length | ***Pan Evaporation*** *= the amount of water evaporated from an open pan per day* **|** ***Hot Days*** *= annual count of days with maximum temperature >35°C* **|** ***Cold Spell Duration*** = Annual count of nights with at least 4 consecutive nights when daily minimum temperature < 10th percentile **|** ***Growing Season Length*** = Annual (*01 July to 30 June) count between first span of 6 or more days with daily mean temperature >15°C and first span of 6 or more days with daily mean temperature <15°C*

Additional climate projections for Queensland

- Global atmospheric **carbon dioxide concentration** (CO_2) is rapidly increasing. In March 2015, the monthly global average carbon dioxide concentration exceeded 400 ppm, well above the natural historical range from the last 800,000 years of 172 ppm to 300 ppm (CSIRO and BOM 2012). Global CO_2 levels are projected to reach 540 ppm by 2050 and 936 ppm by 2100 (RCP8.5 high emissions) (IPCC 2013).
- Queensland can expect **longer dry period**s interrupted by **more intense rainfall** events. The frequency of both extreme El Niño and extreme La Niña events are likely to nearly double in response to greenhouse warming (Cai et al. 2014, 2015).
- Although there is some uncertainty about future **tropical cyclone** potential in Queensland, there is confidence in the projections of a future decrease in the frequency of tropical cyclones, an increase in the proportion of high intensity tropical cyclones and a decrease in the proportion of mid-range intensity storms: more than 50% of models project a decrease in the frequency of tropical cyclones of between 15 to 35% by 2090 (CSIRO and BoM 2015).
- Along the Queensland Coast, **sea level** is expected to rise 13 cm (the model range is 8 – 18 cm) by 2030 and 65 cm by 2090 under the highest emissions (CSIRO and BoM 2015). The Statutory erosion prone areas are declared under section 70 of the *Coastal Protection and Management Act 1995* (Coastal Act) and include the effect of a projected 80 cm sea level rise. An 80 cm rise in sea level is expected to inundate about 1.25 Mha of Queensland (which is 173 Mha in size); or about 119,434 ha (1.3%) of the Whitsunday, Hinterland and Mackay region land (8.97 Mha) which consists mainly of existing marsh/wetland (0.9%) and natural grazing land (0.2%) (DSITIA 2012, Witte et al. 2006).
- Since 1750, atmospheric **CO_2** dissolving in the oceans has lowered the global average **ocean pH** by 0.1 units, representing a 30% increase in hydrogen ion (acid) concentration (Howard et al. 2012). Ocean pH is expected to decrease a further 0.2-0.5 units by 2100 lowering rates of calcification for shelled marine organisms (Caldeira and Wickett 2005).
- **Ocean circulations** are expected to change, including a possible intensification and strengthening of the East Australian Current by a further 20% by 2100 (Poloczanska et al. 2009, Cai et al. 2005). However, a more recent study showed differences in strengthening between regions with most of the strengthening likely to occur south of the Great Barrier Reef (Sun et al. 2012).
- **Sea surface temperature** off the Queensland coast is most likely going to be between 0.4-1°C warmer in 2030 and 2.5-3.0°C warmer by 2090 than the 1986-2005 baseline (CSIRO and BOM 2015).
- The amount of time spent in **extreme drought** will increase in the highest emission scenarios (CSIRO and BOM 2015).

Table 2: Historical means for the period 1986-2005 and climate projections for 2030 (2020-2039) under the RCP8.5 emissions scenario relative to the model base period of 1986-2005

Variable		Annual	Summer	Autumn	Winter	Spring
Temperature (°C)	Historical mean	22.5	27.1	22.7	16.8	23.5
	Projections for 2030	+1 +0.5 to +1.4	+1 +0.5 to +1.6	+1 +0.2 to +1.4	+1 +0.5 to +1.6	+1 +0.4 to +1.4
Rainfall (mm)	Historical means	689	343	164	76	108
	Projections for 2030	-8% -22% to +8%	-5% -35% to +21%	-6% -31% to +15%	-15% -47% to +23%	-9% -42% to +16%
Potential Evaporation (mm)	Historical mean	1734	**Historical means from 1986-2005** **Projections for 2030 (20-year period centred on 2030)** **Best Estimate** **Range of Change (5th - 95th)** *For more information, including projections for 2050 and 2070, please refer to http://www.climatechangeinaustralia.gov.au/en/ or McInnes et al. 2015.*			
	Projections for 2030	+4% +2% to +6%				
Relative Humidity	Projections for 2030	-1% -4% to +2%				
Wind Speed	Projections for 2030	2% 0 to +22%				

Impacts of a variable and changing climate in the Whitsunday Hinterland and Mackay Region

Whilst a more variable and changing climate will impact the key primary industries in the region, the population and natural environment will also feel the effects.

Human Well-Being

The variable and changing climate of the region will have both direct and indirect impacts on health, location and living arrangements (Marshall 2014).

Likely Impacts	*Potential Strategies for Adaptation*
Extremes of weather and climate (drought, flood, cyclones, heatwaves etc.) on human well-being (TCI 2011, Hughes and McMichael 2011, NCCARF 2011a)	

• Direct effects of extremes of weather include injury and death during floods and cyclones, heat stress during heatwaves, and a reduction of cold-related deaths.
• Indirect effects of extremes of weather could include an increase in the:
  ◦ number of bushfires due to extreme heat and aridity;
  ◦ risk of mosquito-borne, water-borne and food-borne diseases;
  ◦ number of infectious and contagious diseases with an increase in the number of injuries; and
  ◦ incidence of disease from microbial food poisoning with an increase in temperature.
• Increases in extreme events can lead to increased pressure on health systems, including an increased demand for health professionals, ambulance and hospital workers.
• Rural, regional and remote communities are particularly exposed in a changing climate compounding the chronic difficulties and inequities that already face many communities. Many parts of the country already find it hard to recruit dedicated health care and social service professionals. A changing climate will also increase the demand for social support and mental health services, and, at the same time, make it harder to recruit and retain staff in affected areas.
• Infrastructure assets along the Queensland coast and islands are at risk from the combined impact of sea level rise, inundation, shoreline recession, coastal erosion and extreme events (DCCEE 2011).
• Severe weather events can destroy places and disrupt livelihoods and communities leading to long-term mental health effects. According to Bonanno et al. 2010, a significant part of the community, as many as one in five, will suffer the debilitating effects of extreme stress, emotional injury and despair.
• The emotional and psychological toll of disasters can linger for months, even years, affecting whole families, the capacity for people to work and the wellbeing of the community.
• Evidence is beginning to emerge that drought and heatwaves lead to higher rates (by about 8%) of self-harm and suicide (Doherty and Clayton 2011).
• Those most vulnerable to extremes of weather and climate include children, the elderly, Indigenous communities and people with pre-existing diseases and disabilities.
	• Adapt existing buildings and plan any new infrastructure to take into account climate impacts and extreme events such as flooding, tropical cyclones and sea level rise.
	• Implement control measures to reduce the impact of bushfires, heatwaves, mosquitoes, water-borne and food-borne diseases, infectious and contagious diseases and injuries.
	• Continue to obtain information on the expected effects of a changing climate.
	• Develop agreements with your workers on how to manage extreme hot days, or identify periods of time where weather and climate affect working conditions.
	• Develop social support networks.
	• Contact your local council or relevant government department to find information on social and health support programs.

Biodiversity

The Brigalow Belt (BB) and Central Queensland Coast (CQC) bioregions are present within the Whitsunday, Hinterland and Mackay region. The BB is the largest bioregion in Queensland and is very rich in species, including large numbers of plants and animals with small ranges. This bioregion has endemic and near-endemic eucalypt, wattle and invertebrate species. The CQC has many species with small distributions that may face threats from a more variable and changing climate. The mountains within this bioregion serve as refugia for rainforest and wet eucalypt forest species. There are several endemic or near-endemic species including nine lizard species, two frog species, the Proserpine Rock Wallaby (*Petrogale persephone*), the Eungella honeyeater (*Lichenostomus hindwoodi*) and various invertebrate and plant species. The impacts of climate change on biodiversity in the region will introduce new stressors to species and ecosystems, and in some regions, impacts are already evident (Reside et al. 2014, Williams et al. 2014).

Likely Impacts	***Potential Strategies for Adaptation***
Extremes of weather and climate (drought, flood, cyclones, heatwaves etc.) on Biodiversity (Low 2011)	
<u>Impacts in the Brigalow Belt</u> • Severe drought in the BB may result in deaths of many trees including Brigalow and Cypress pines. • Buffel grass invasion is of particular concern within the BB. Invasion of this species may displace groundcover plants and significantly increase fire risk. <u>Impacts in the Central Queensland Coast</u> • Buffel grass invasion is of particular concern with invasion of this species displacing groundcover plants and increasing risk of intensive fires. • On the CQC, the rainforests support endemic frogs, lizards and invertebrates. Many of these species face high risks from a changing climate, and rainforests habitats could be directly damaged by cyclones of unprecedented severity.	• Fire management. • Manage weeds and flammable invasive pasture grasses, such as buffel grass and gamba grass, in and near conservation areas. • Control pests and feral animals (goats, horses) to reduce losses and protect rare plants. • Protect refugia habitats. • Replant upland rainforests to increase the chances of montane animals surviving varying climates. • Control pigs to prevent the spread of *Phytophthora cinnamomi* and to help rainforest lizard, frog and invertebrate populations.

Grazing Industry

Cattle, sheep and wool are important primary industries in Queensland. In 2014-15 their combined GVP was $5.2 B (44% of the total Queensland GVP of agricultural commodities, ABS 2016a) which is made up of the production and marketing of beef cattle ($5.1 B), sheep and lambs ($66.4 M) and wool ($66.2 M).

Cattle numbers in WHM were 145,300 in 2014-15 which was 1% of the total cattle numbers for Queensland (ABS 2016b). In 2014-15 the GVP for cattle, sheep and wool for WHM was $65 M (ABS 2016a) or 15% of the value of WHM agricultural commodities.

The majority of beef, sheep and wool production come from native pastures which cover about 85% of Queensland. The main pasture communities in WHM are Black Spear grass (28% of region), Aristida-Bothriochloa (21%) and Brigalow pastures (13%) (Tothill and Gillies 1992). The soil fertility is excellent (Brigalow) to poor (Aristida-Bothriochloa) and growth of pastures is usually limited by inadequate rainfall (Black spear grass, Brigalow) or low nitrogen availability (Aristida-Bothriochloa).

There are climate change impacts specific to the Wet Tropics region and regionally specific adaptation options some of which will offset negative impacts and other that will enable opportunities to be had (Langston and Turton 2014).

Case Study – Impacts in the Whitsunday, Hinterland and Mackay Region

The impacts of a changing climate are complex because of interacting and opposing forces operating within the biophysical system (McKeon et al. 2009). The process of assessing the impacts of a changing climate often involves deriving the 'best estimate' projections of future climate, simulating the grass growth and grazing strategies under changing climate conditions using well-calibrated grass/grazing system models, and combining the simulation output with successful producer and researcher experience in regional Queensland. A good example of a proven process of assessing the impacts, adaptive responses, risks and vulnerability associated with a changing climate is the 'risk matrix' approach (http://www.longpaddock.qld.gov.au/products/matrix/index.html, Cobon et al. 2009, 2016) which is customised for primary industries and is based on the Australian and New Zealand Risk Management Standards (Standards Australia 2004).

There are many gaps in knowledge, for example, the future climate projections are uncertain (particularly for rainfall) and in some cases the projected changes in rainfall and temperature appear smaller than year-to-year variability. Nonetheless, a risk-averse approach to grazing management based on the 'best estimate' projections in combination with short-term management of climate variability is likely to take advantage of any opportunities and reduce the risk of adverse impacts. There are major known uncertainties in identifying the impacts of a changing climate in the grazing industry in relation to:

1) carbon dioxide and temperature effects on pasture growth, pasture quality, nutrient cycling and competition between grass, trees and scrubs;

2) the future role of woody plants including the effects of fire, climatic extremes and management of stored carbon (see McKeon et al. 2009 for more detail); and
3) carbon dioxide effects on diet quality and liveweight gain of cattle (Stokes 2011).

Modelling analyses of native pasture grasses (C4 tropical and sub-tropical grasses) for the WHM region were undertaken for the Clermont, Collinsville and Nebo areas (Cobon et al. 2012 *unpublished data,* Table 3). The average impacts of future climate scenarios from the three locations were examined for pasture growth, pasture quality (% nitrogen of growth), liveweight gain of cattle (LWG kg/ha), frequency of burning and frequency of green pasture growing days (GPGD). The baseline climate period was 1960-1990 and carbon dioxide concentration was 350 ppm. Improvements in water and nitrogen use efficiency resulting from doubling of carbon dioxide levels were accounted for in the modelling as per Stokes 2011. The impacts were either positive or negative, and as a guide were also classified as being of either High (>20% change from baseline, H), Medium (5%-20%, M) or of little or no impact (5 to -5%, LC). The soils were of average fertility (20 kgN/ha) and the density of trees (8.55 m^2/ha tree basal area) resembled that of open woodland.

Table 3: Matrix showing potential opportunities and risks associated with the average impacts of future climate scenarios from Clermont, Collinsville and Nebo for modelled pasture growth (kg/ha), pasture quality (% nitrogen in growth), liveweight gain of cattle (LWG kg/ha), frequency of burning and green pasture growing days (GPGD) (Source: Cobon et al. 2012 *unpublished data*).

Future climate	Growth	Quality	LWG	Burning	GPGD
+3°C	-M	+M	-M	-M	LC
2xCO_2	+M	-M	+H	+M	LC
+3°C, 2xCO_2	+M	-M	+M	+M	+M
+3°C, 2xCO_2, +10% rainfall	+M	-M	+H	+M	+M
+3°C, 2xCO_2, -10% rainfall	LC	LC	LC	-M	LC

H= high, M= medium, LC = little change
Shading indicates positive and negative impacts
Positive impacts showing either High or Medium opportunities
Negative impacts showing either High or Medium risks

This study found that:

- the benefits of doubled carbon dioxide and the combined effects of a 3°C rise in temperature, doubled carbon dioxide and 10% more rainfall associated with pasture growth, liveweight gain and frequency of burning outweighed the disadvantages caused by a 3°C rise in temperature;
- doubled carbon dioxide and the combined effects of a 3°C rise in temperature, doubled carbon dioxide and 10% more rainfall is likely to reduce pasture quality; and
- green pasture growing days are likely to increase with the combined effects of a 3°C rise in temperature and doubled carbon dioxide, and a 3°C rise in temperature, doubled carbon dioxide and 10% more rainfall.

Cattle Muster, Nebo, Queensland

Courtesy of Tourism Queensland

Opportunities for the Grazing Industry

- Increased production of biomass will result from rising carbon dioxide levels as plants use water, nutrients and light resources more efficiently (Nowak et al. 2004).
- Improved plant water use efficiency will allow pastures to produce more biomass using the same amount of water (Stokes et al. 2011).
- Elevated carbon dioxide will increase the efficiency of water and nitrogen use by the pastures (Stokes et al. 2008), but this increase in growth of pastures is likely to be offset by a reduction in overall pasture quality (lower protein and lower digestibility) (Stokes et al. 2011).

Case Study – Impacts in nitrogen-limited areas

Although the carbon dioxide effects on forage production in nitrogen limited land types are uncertain, it is likely that elevated carbon dioxide will lead to improved nitrogen use efficiency in forage growth and lower minimum nitrogen concentrations in the forage, which is likely to reduce liveweight gain of livestock, increase the risk of wildfires and increase the importance of prescribed burning (Stokes et al. 2011).

Case Study – Using past records to help understand future impacts

Projected changes in rainfall of the order of ±10% appear low compared to year-to-year variability, or even in the difference between the average of El Niño and La Niña years (-20% and 20% rainfall respectively in eastern Australia) (McKeon et al. 2004). However, when the historical range of variation is analysed for a 25-year (climate change time-scale) moving average then a change in rainfall of ±10% is relatively high. For example, the 25-year moving average of rainfall at Clermont has fluctuated between -12 and +16% compared with the long-term average since 1871 (Figure 1). The extended periods of lower rainfall (1930s to 1950s, late 1960s to early 1970s, 1980s, and 2000s) have been associated with extensive droughts, degradation events, reduced profits and greater debt and human hardship. It is likely that under drier climatic conditions these circumstances will become more familiar with shorter and less frequent recovery periods.

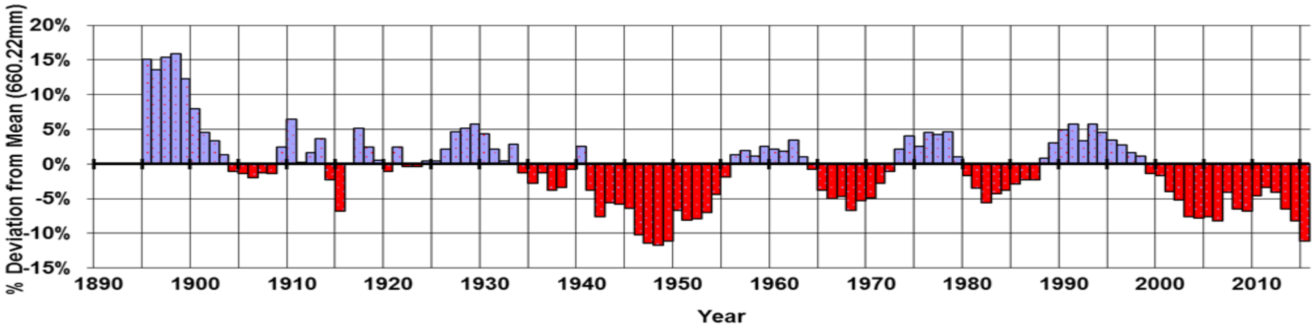


Figure 1: 25-year moving average rainfall (12 months, April in year 1 to March in year 2) at Clermont, Qld (Source: Clewett et al. 2003).

Likely Impacts	*Potential Strategies for Adaptation*
Changed rainfall patterns	

• Longer and more frequent droughts associated with more extremes of climate, fewer recovery events, changes in decadal rainfall variability and ENSO will decrease forage production, surface cover, livestock carrying capacity, animal production and cause major changes in plant and animal species compo-sition (Cobon et al. 2009, McKeon et al. 2009).
• Erosion risks are likely to increase due to greater year-to-year variability in rainfall.
• Rising tree densities and declining pasture condition raise the sensitivity of pastures to climate induced water stress.
	• Manage perennial grass cover using 'best management practice' for the pasture community. For example, set the annual stocking rate at the end of each growing season to utilise a safe proportion (10-20%) of available pasture and make adjustments accordingly for beneficial or spoiling rainfall in winter or spring, early breaks to the dry season, locust plagues and forecasts of rainfall for the coming summer.
	• Monitor trends in rainfall.
	• Use climate indicators to make early adjustments in animal numbers.
	• Manage non-domestic grazing pressure.
	• Use wet season spelling of pastures.
	• Manage invasive plant species.
	• Maintain refugia especially around wetlands (Cobon et al. 2009).
	• Manage climate variability and change by using forecasts of rainfall (and temperature) in decision making.
	• Manage intra-seasonal (MJO, 30-60 day cycle), inter-annual (ENSO, 2-7 year cycle) and decadal rainfall variability (PDO/IPO, 20-30 year cycle) using indicators of MJO, ENSO (SOI, SST) and PDO, and climate analysis tools to adjust animal numbers commensurate with past and projected climate trends, such as:
	  o LongPaddock (http://www.longpaddock.qld.gov.au);
	  o AussieGRASS (http://www.longpaddock.qld.gov.au/about/researchprojects/aussiegrass/index.html);
	  o ClimateArm http://www.armonline.com.au/ClimateArm
	  o Bureau of Meteorology Website http://www.bom.gov.au, http://reg.bom.gov.au/climate/mjo
	• Use supplementary feeding, early weaning and culling animals at risk to reduce mortalities in dry conditions (Fordyce et al. 1990). Increase or maintain *Bos indicus* content in herd to increase cattle tick and buffalo fly resistance/resilience.
	• Monitor spread of pests, weeds and disease.
	• Introduce more species of dung fauna (control of buffalo fly larvae).
	• Promote greater use of traps and baits (buffalo and sheep blowflies) and vaccines (cattle ticks and worms).
	• Use fire to control woody thickening.

Likely Impacts	*Potential Strategies for Adaptation*
Increased temperatures	
Warming will be greatest toward the interior of the continent away from the moderating influence of the ocean. Each 1°C increase in temperature will cause a warming that would be roughly equivalent to moving about 145 km (or about 2° in latitude) closer to the equator (Stokes et al. 2011). For example, Clermont under warming of 3°C is likely to receive temperatures currently experienced at Kowanyama (Figure 2). • Livestock will be exposed to a greater risk of heat stress. They are unlikely to travel as far to water which concentrates grazing pressure and increases the risk of adverse pasture composition changes and soil degradation (Howden et al. 2008). • Increased day time temperatures increases water turn-over and evaporative heat loss resulting in reduced rate of passage and forage intake in livestock (Daly 1984). • Increased night time temperatures can reduce recovery time of livestock and increase the effects of heat stress during the day. • Increased heat stress reduces fertility, conception, peri-partum survival and follicle development in sheep. • Warmer conditions favour vectors and the spread of animal disease (White et al. 2003). • Pastures could cure earlier under warmer climates shifting the timing of fires to earlier in the season. • Warmer drier conditions with higher frequency of storms could increase the risk of wildfires.	• Arrange water points to reduce distance to water and even out grazing pressure. • Select the time of mating to optimise nutritional requirements and reduce the risk of mortality in new-borns. • Select cattle lines with effective thermoregulatory controls, efficient feed conversion and lighter coat colour (Finch et al. 1984, King 1983). • Proactively control disease by targeting known sources of disease and vectors (Sutherst 1990). • Maintain high standards of animal welfare to build domestic and export meat and fibre markets (Mott and Edwards 1992). • Incorporate greater use of prescribed burning to reduce the risk of wildfires and control woody thickening. • Rotate paddocks of heavier grazing for use as fire breaks. • Maintain or improve quarantine capabilities, monitoring programs and commitment to identification and management of pests, disease and weed threats. • Develop species resistant to pests and disease, and use area-wide improved management practices.

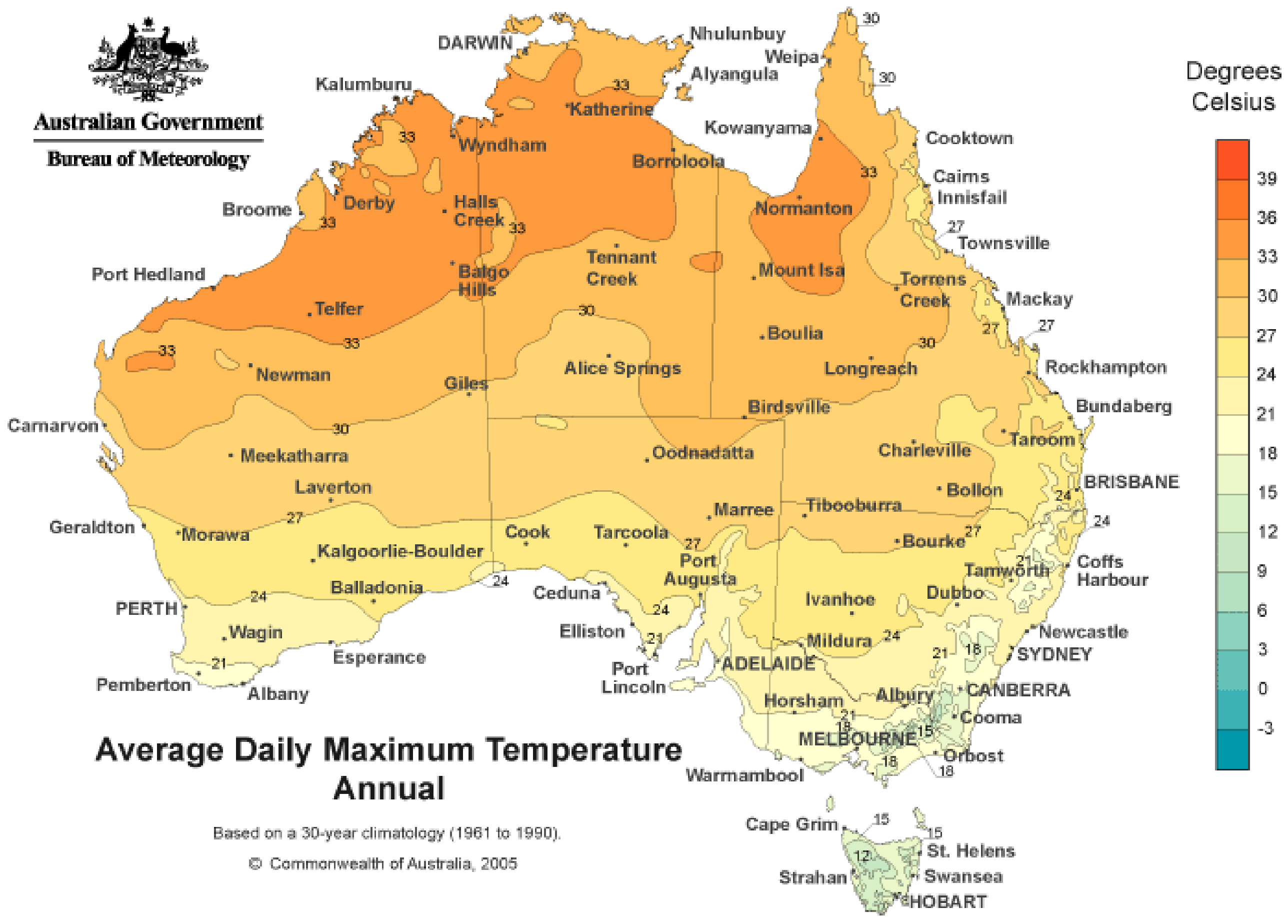


Figure 2: Annual average temperature in Australia (Source: Bureau of Meteorology). One degree of warming is roughly equivalent to moving 145 km toward the equator.

Likely Impacts	*Potential Strategies for Adaptation*
Increased temperature, higher carbon dioxide concentration and changed rainfall	
• Pastures growing under a climate characterised by consistent water stress appear to benefit most from increased plant water use efficiency under elevated carbon dioxide. • The fertilisation effects of doubled carbon dioxide (700 ppm) were found to offset declines in forage production under 2°C warming and a 7% decline in rainfall (Webb et al. 2011). • The combined effects of elevated carbon dioxide (650 ppm), higher temperature (3°C) and lower rainfall (10%) resulted in 10-20% lower forage production (McKeon et al. 2009). In this study increased temperature and declining rainfall outweigh the conservatively represented benefits of increasing carbon dioxide. • Rising carbon dioxide will result in a reduction in overall pasture quality (lower protein and lower digestibility) (Stokes et al. 2008).	• Maintain land in good condition to reduce potential declines in forage production under a warmer drier climate. • To compensate for declining forage quality, increase the use of supplements (N, P and energy) and rumen modifier. • Destock earlier in the season to make greater use of feedlots to finish livestock. • Explore alternative land use in marginal areas. • Apply safe carrying capacity of ~10-15% utilisation of average long-term annual pasture growth. • Undertake risk assessments to evaluate needs and opportunities for changing species, management of land and land use. Support assessments of the benefits and costs of diversifying property enterprises. • Introduce pasture legumes to improve nitrogen status.
More intense storms	
• Rainfall intensity is expected to increase as temperature and moisture content of the atmosphere increase. • A 1°C increase in temperature may result in an increase in rainfall intensity of 3-10% (SAG 2010). • More intense storms are likely to increase runoff, reduce infiltration, reduce soil moisture levels and pasture growth, and increase the risk of soil erosion.	• Maintain pasture cover for optimal infiltration of rainfall. • Adjust livestock numbers to maintain good coverage of perennial pastures during the storm season.
Higher temperature humidity index (combination of maximum temperature and dewpoint temperature)	
• Temperature humidity index (THI) is an indicator of heat stress. Heat stress in beef cattle is significant at a THI of over 80. Frequency of days per year above this level is shown in Figure 3 for historical and projected climate. Rising temperature by 2.7°C increases the occurrence of heat stress by about 30% points (Howden et al. 1999). • Heat stress reduces liveweight gain and reproductive performance in beef cattle, and increases mortality rates (see Howden et al. 1999). • Heat stress reduces the development of secondary wool follicles in sheep, reducing lifetime wool production in sheep (Hopkins et al. 1978).	• Select cattle lines with effective thermoregulatory controls, efficient feed conversion and lighter coat colour (King 1983, Finch et al. 1984).

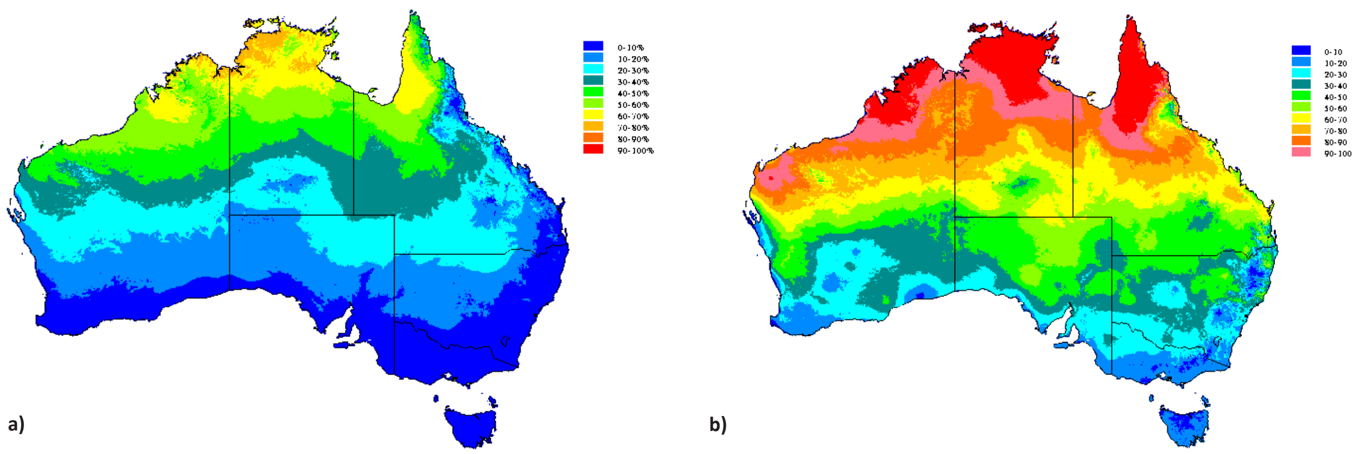


Figure 3: Frequency of days per year that the THI>80 for a) 1957-97 and b) a future climate scenario of +2.7°C. Thermal stress is significant in beef cattle when the THI exceeds 80 (Source: Howden et al. 1999).

Sugarcane on the Peak Down Highway, Mackay, Queensland Courtesy of Tourism Queensland

Horticulture Industry

Horticulture is Queensland's second largest primary industry (QFF 2012. Queensland grows approximately one third of Australia's horticulture produce, with more than 120 different types of fruit and vegetables being grown in 16 defined regions covering a total area of 100,000 hectares and 2800 farms (QFF 2012, HAL 2012). In 2014-15 the value of production for Queensland was about $2.5 B which was made up of $1 B for vegetables, $1.2 B for fruit and nuts and $290 M for nurseries, cut flowers and turf (ABS 2016a).

In 2014-15 WHM produced about 1% of the total value of the state's horticulture, including 1% of the value of vegetables and 1% of the value of nurseries, cut flowers and turf (ABS 2016a).

Much of the information below on the impacts of a changing climate for the horticulture industry is drawn from reports commissioned for the Garnaut Review (Deuter 2008).

Opportunities for the Horticulture Industry

Capsicum and chillies grow best when temperatures are between 20°C and 30°C so higher minimum temperatures in winter may increase growth and reduce time to harvest, although increased maximum temperatures may result in flower buds falling off and reduced yield.

Case Study – Wet season cover crops maintain ground cover for horticulture crops

On a 400 ha farm, 40 km north of Proserpine, half of which is used for cattle, the other half for eggplant, pumpkin and melon, cover crops, such as sorghum, have been planted in the fallow to maintain ground cover during the wet season. Cover crops have decreased the risk of sediment and particulate nutrient loss (Reef Catchments 2010).

Likely Impacts	*Potential Strategies for Adaptation*
Increased temperatures	
• Changes to the suitability and adaptability of some crops. • Potential shift in the period for winter vegetable production. • Change the timing and reliability of plant growth, flowering, fruit growth, fruit setting, ripening and product quality; fruit size, quality and pollination. • Change harvesting times for different areas. • Reduce the time to reach maturity (earlier in the season). • Change the occurrence and distribution patterns of fruit fly and *Helicoverpa*. • Potentially downgrading product quality. • Result in pollination failures. • Increase active soil-borne diseases and insect infestation for longer periods during the year. • May affect the post-harvest quality for horticultural crops that are required to be cooled so as to remove field heat quickly. • Reduced diurnal temperature range will potentially reduce the overlap between open stages of male and female flower parts thus decreasing the chances for pollination and resulting in more pollination failures, fruit drop and sunburn to fruit. • Increased minimum temperatures and reduced occurrence of frost may benefit some crops, e.g. grapes, and negatively impact vegetable growers in tropical and sub-tropical regions producing winter crops as the winter production season will be shortened. • Changes in disease and pest distribution ranges.	• Select for, or change to, cultivars which are more adaptable to a changing and variable climate. • Select and review growing site/location to avoid unsuitable climate factors through identifying threshold temperatures or other climate conditions for crops. • Choose optimal timing of planting. • Use chemical treatments such as hydrogen cyanamide to induce bud break to manage the variable and non-uniform budburst and to protract full bloom of pip, stone fruit and nut trees if dormancy is affected. • Start breeding program for heat tolerant, low chill and more adaptable varieties of various horticultural crops. Varieties with higher quality under enhanced carbon dioxide and elevated temperatures will need to be evaluated then considered in breeding programs. • Apply the latest research results and best management techniques to maintain product quality. • Use crop protection treatments including solar radiation shading and evaporative cooling through overhead irrigation to maintain fruit quality. • Use tools/models associated with managing climate variability to improve both quality and quantity of horticulture products. • Consider growing frost-sensitive fruit in regions previously considered unsuitable due to frost risk, e.g. expansion of areas for growth of tropical and sub-tropical crops such as citrus, avocados, bananas and pecan nuts. • Plant varieties with chilling requirements below 1000 hours.

Changed rainfall patterns	
• Increased risk to crops reliant on irrigation where irrigation water availability is reduced especially during dry periods. • Changes to the reliability of irrigation supplies, through impacts on recharge to surface and groundwater storages.	• Adopt more efficient irrigation monitoring and scheduling technologies which provide further water-use efficiencies. • Apply the latest research results and best management techniques to maintain product quality, including fertiliser timing and amounts according to crop requirements. • Use tools/models associated with managing climate variability to improve both quality and quantity of horticulture products.
More intense storms	
• Increased runoff may provide opportunities for growers to capture more water for irrigation. • Lead to conditions favouring foliar diseases and some root invading fungi, for example, the fungus *Phytophthora cinnamo-mi*, which affects avocado. • Increase the likelihood of crop damage and waterlogging, decreasing quality and production. • Affect the timing of cultural practices and ability to harvest, as well as negative effects on yield and product quality. • Increase the risk of the spread and proliferation of soil borne diseases; soil erosion and off-farm effects of nutrients and pesticides; affected water quality and impacts on other ecosystems (e.g. Great Barrier Reef).	• Improve Integrated Pest and Disease Management practices to adapt to a changing climate and encourage disease sup-pressive soil techniques. • Improve on-farm water storage linked to drainage and water harvesting systems. • Improve sediment runoff protection via grassed waterways and erosion control structures. • Improve plant nutrition management. • Improve all-weather access to cropping areas.

Sugar Industry

Australian sugarcane is grown in Queensland and northern New South Wales and the industry consists of 4000 cane farming businesses, 24 mills and six bulk storage ports (Canegrowers 2011). Ninety-five percent of Australian sugarcane is grown in Queensland and 85% is exported (QLDDAFF 2010).

In 2014-15, 30 M tonne of cane was produced in Queensland (ABS 2016b) with a value of $1.2 B of which 28% was produced in WHM (ABS 2016a).

Much of the information below on the impacts of a changing climate on the sugar industry is drawn from Stokes and Howden (2010) and references therein.

Opportunities for the Sugar Industry

- Increased temperatures and carbon dioxide are likely to lead to accelerated crop development, increased yield and an extended growing season.

Case Study – The delayed impact of the 2010 (extremely) wet season on sugarcane

In September 2011, canefarmers were starting to feel the full impact of the 2010 wet season. The 2010 wet conditions meant that a large amount of cane was unable to be crushed and was left in the field as standover. As a result, the overall tonnage for 2011 was 23 Mt, about 10 Mt less than average (Hunt 2011).

Likely Impacts	*Potential Strategies for Adaptation*
Increase in atmospheric carbon dioxide	
• Increased growth of stalk and total biomass. • Increased competitiveness from C3 weeds (e.g. temperate grasses). • Increased growth of vegetative plant parts (i.e. increased volume of trash). • Higher carbon to nitrogen ratio of leaves.	• Optimise supply of all necessary resources to the crop. • Use bio-control agents, cultural practices and expert systems for improved weed and crop management. • Use or breed suitable varieties with improved future climate yield characteristics (high sugars). • Adopt an integrated pest management system.

Increased temperatures	
• Yields may decrease as a result of increased heat and evaporation, stomatal closure and leaf damage. However, increased carbon dioxide may override these effects. • Sucrose content may decrease as a result of higher temperatures during the harvest season. • Incidence of pests and diseases may increase through better survival of populations during winter periods, the spread of exotic populations into wider climatic windows and altered ecological interactions with natural enemies. • Increased carbon decomposition and soil nitrogen mineralisation. • Increased crop energy diverted into producing trash and fibre.	• Lengthen the period of harvest time to increase yield, or grow additional fallow or cash crops. • Reduce excessive biomass accumulation by planting later and emphasising erect growth habit in breeding and variety selection. • Use varieties with greater tolerance to higher temperatures. • Optimise supply of all necessary resources. • Alter the duration of the harvest season to coincide with cooler temperatures. • Use adapted varieties and management practices, i.e. irrigation scheduling in favour of sucrose accumulation and use ripeners to better manage sugar accumulation. • Change cultural practices to reduce pests and disease (e.g. use legume crops to break soil pest and disease cycles) and reduce vegetative growth (e.g. reduce water use from irrigation). • Change insecticides, fungal and bacterial bio-pesticides. • Use varieties with improved resistance to pests and diseases. • Use integrated pest management. • Use decision support software. • Revise quarantine boundaries. • Consider implementing pest strategies presently used by more northerly regions. • Review soil carbon and nitrogen management practices. • Use precision agriculture and legume crops to boost soil organic carbon and nitrogen stores. • Use varieties with low vegetative growth habits and stalk fibre content.

Reduced rainfall	
• Limited supply of irrigation water. • Reduced soil anaerobic conditions and nutrient loss through less leaching and erosion. • Increased commercial cane sugar through more effective drying-off period. • Increased traffic-ability for harvest machinery and the timeliness of operating. • Poor crop establishment. • Decreased yields as a result of increased crop water stress. • Reduced quality of supplementary water. • Reduced rate of early leaf area and canopy development. • Reduced photosynthesis, tillering and stalk length.	• Increase use of supplementary water. • Optimise irrigation scheduling. • Use more effective irrigation water delivery technologies (i.e. trickle tape). • Construct on-farm water storage. • Use drought-tolerant or more water efficient varieties. • Modify row spacing. • Minimise tillage. • Use cover crops. • Optimise availability of all resources (possibly through precision agriculture). • Adopt efficient irrigation technology to control water table. • Monitor water table position. • Improve catchment vegetation distribution and ground cover to increase infiltration rate.

The General Gordon Hotel, Homebush, Queensland

Courtesy of Tourism Queensland

More intense storms, increases in rainfall intensity and rising sea levels	
• Increased physical damage to crops and infrastructure. • Increased flooding, land degradation and damage to infrastructure. • Exacerbation of storm and cyclone damage. • Increased soil erosion and nutrients and sediment load to the Great Barrier Reef Marine Park. • Increased intrusion of saltwater into coastal aquifers. • Decreased yield through reduced infiltration of rainfall into soil.	• Plant trees around the paddock to act as a windbreak. • Use harvesting machinery suitable for harvesting a lodged crop. • Use varieties with reduced propensity to lodging. • Adopt cultural practices to reduce lodging (e.g. hilling up). • Diversify crops with a shorter duration. • Utilise insurance and reinsurance options to offset risk. • Use trash blanketing to intercept rainfall, inhibit lateral movement of water, reduce evaporation, improve soil structure and water infiltration and increase soil carbon stores. • Use conservation tillage to reduce soil compaction. • Alter row configurations. • Use drainage ditches and laser levelling to control localised flooding and retain surface water, nutrients and sediment. • Increase use of precision farming, adopt conservation tillage methods. • Construct man-made seawater defences and investigate new regions to plant sugarcane. • Restrict groundwater pumping. • Abandon bores already impacted by saltwater intrusion. • Monitor water quality in aquifers. • Investigate new regions to plant sugarcane.

Mango and Scallop Entree, Hamilton Island, Queensland — Courtesy of Tourism Queensland

Fishing Industry

The majority of Queensland fisheries extend the entire length of the east coast, with a few fisheries also located in the Gulf of Carpentaria. The highest value Queensland fishery, the East Coast Otter Trawl Fishery, targets nine prawn species, two bug species, two lobster species, two crab species and a variety of other crustaceans, plus several species of molluscs (Fisheries Queensland 2016. In the 2014 season, the total harvest for this fishery (including recreational, indigenous and charter fishing) was 6681 tonnes with a gross value of production (GVP of $86 million. The next highest value fisheries are three line fisheries which cover the entire Queensland coast line, including the Gulf of Carpentaria. These fisheries target a variety of fish species and have an approximate total harvest of 6300 tonnes and GVP of $38 M.

Much of the information below on the impacts of a changing climate on the fishing industry is drawn from Holbrook and Johnson (2014, Hobday et al. 2008, Johnson and Marshall 2007 and NCCARF 2011b).

Opportunities for the Fishing Industry

- Increased nutrient influx, multiple spawning events and participation in fishing.
- Increased abundance and catch rates of some target prawn and bug species due to possible biomass and growth increases with rising temperatures.

Case Study – The impacts of increased temperatures on redthroat emperor in the Great Barrier Reef

Sweetlip or redthroat emperor (*Lethrinus miniatus*) appears to be restricted to south of 18°S due to its apparent upper thermal limit of about 28°C. Its longevity of about 20 years means it is unlikely to adapt quickly to environmental change. The distribution of *L. miniatus* on the GBR is therefore expected to be reduced as temperature increases (Johnson and Marshall 2007).

<table>
<tr><th>Likely Impacts</th><th>Potential Strategies for Adaptation</th></tr>
<tr><td>Increased carbon dioxide levels and ocean acidification
• Degradation of reef habitats may lead to a decrease in small reef fish. This may impact higher trophic level species which may be important for recreational and commercial fisheries (Munday et al. 2008, Pratchett et al. 2008). Ocean acidification may have impacts on the olfactory cues of some tropical fish species, impacting connectivity and ability to migrate (Booth et al. 2009).</td><td rowspan="4">• Incorporate climate risk management into Ecosystem-Based Fishery Management including further developments in bycatch reduction and improved targeting practices.
• Implement responsive business practices and management amendments including:
  ○ improving fishing technology including technology to locate stock and communicate with other boats and people on land;
  ○ reviewing sustainable and precautionary harvest levels;
  ○ building resilience through improved stock status;
  ○ improving spatial management including zoning of fish habitats to minimise unwanted species interactions and closures; and
• Using predictive models for estimating harvest levels (Hobday et al. 2007b).
• Make seasonal changes to home port to minimise economic costs associated with transport.
• Develop programs to restore and protect fish habitats, breeding grounds, nursery habitats and fish refugia.
• Increase environmental flow allocation and water aeration.
• Implement operational changes including fleet restructuring, optimising catch per unit effort and diversifying income streams.
• Develop a new business model that enables fewer fishing days to increase responsiveness to good weather.</td></tr>
<tr><td>Increased ocean temperatures
• Changes to reproduction, life history traits, catchability and fish behaviour (Voice et al. 2006) may occur.
• In freshwater dependent fisheries, impacts may include earlier spawning, skewed sex ratios and decreases in oxygen levels.
• In both freshwater and marine fisheries, there may be changes to the distribution of species, range expansions and contractions, and modified tolerance to normal temperature changes.
• There may be a southern distribution shift of some species, which may increase the risk of competition between resource users.
• Established fishing grounds may decrease in size or be replaced with other species leading to changed profitability.</td></tr>
<tr><td>Changed rainfall patterns
• A decrease in rainfall may lead to an altered nutrient supply in near-coastal habitats, which may lead to changed spawning timing and availability of recruits (Voice et al. 2006).
• The penaeid prawn fisheries and other estuarine-dependent fisheries may be sensitive to changes in rainfall and freshwater flow.
• Changes to freshwater flow patterns may change nutrient runoff, which may affect productivity.
• In freshwater dependent fisheries, decreases in rainfall and subsequent drought may lead to decreased participation in the industry and, therefore, decreased input into the local economy.
• There may be decreases in natural recruitment, growth rates and connectivity, and increases in the number of natural fish deaths.
• Between January and March in the year immediately following an El Niño event there may be enhanced vulnerability of the reef to coral bleaching reducing fish habitat and health of the reef.</td></tr>
<tr><td>More intense storms, rising sea levels and changes to ocean circulation
• In trawl fisheries, more frequent and intense storms may lead to a decrease in the number of fishing days, fishing opportunity, reduced effort and an increase in the need for more robust equipment.
• There may be potential impacts on coastal habitats (e.g. mangrove forests, estuarine and river systems and seagrass beds) which provide important breeding and nursery grounds for prawns, crab and fish.
• The extent of mangrove areas and connectivity between habitats may be reduced.
• Sea level rise and inundation will impact estuarine species and river fish populations (Voice et al. 2006, Booth et al. 2009).
• Changes to ocean circulation may have potential impacts on larval transport among reefs and on the distribution and production of plankton, which may reduce the growth, distribution, reproductive success and survival of larvae, pelagic fishes and reef-associated fishes.
• Changes to ocean circulation may change patterns of fish migration taking stocks away from traditional fishing grounds.
• An increase in the severity of tropical cyclones will cause increased damage to reefs and negatively impact on reef line fishers' productivity.</td></tr>
</table>

Aquaculture Industry

In 2014-15, the aquaculture industry in Queensland was worth $120 M (Fisheries Queensland 2015). The two largest components include prawns and barramundi. Other species harvested include jade perch, redclaw, silver perch, eels, black tiger and kuruma prawns, mud crabs and rock oysters. In 2014-15, the estimated farm-gate value of the Australian prawn industry was $83 M (4950 tonnes); while the Australian barramundi sector was worth $28 M (Fisheries Queensland 2015).

Much of the information below on the impacts of a changing climate on the aquaculture industry is drawn from Hobday et al. (2008) and Johnson and Marshall (2007).

Opportunities for the Aquaculture Industry	**The positive impact of increased temperatures on farmed prawn productivity**
• Rising temperatures may extend the cultivation area suitable for farming these species further south. • The production systems for native warm water fish and crayfish, which consist of static earthen ponds that reuse fish effluent water, will more easily adapt to more variable temperature and limited future water supplies.	Increasing atmospheric temperature and resulting higher water temperature may increase production efficiency of tropical and sub-tropical species of farmed prawns, such as *Penaeus monodon* and *P. merguiensis* (Hobday et al. 2008). Studies have shown that during prolonged periods of warmer pond water, growth rates of tiger prawns (*P. monodon*) were observed to be around the maximum (Jackson and Wang 1998).

Likely Impacts	***Potential Strategies for Adaptation***
Increased acidification (carbon dioxide and pH) • Increased acidification and warmer temperatures may adversely impact growth and reproduction although some spe-cies may be able to adapt to the change. • Increased acidification may lead to decreased calcification and growth rates in some species.	• Selective breeding for tolerance to, or the use of alternate species that are pre-adapted to, altered temperature, water and salt regimes. • Use of dedicated sedimentation ponds (Jackson et al. 2003 in Hobday et al. 2008). • Relocation of production facilities and associated infrastruc-ture. • Raise bund walls around farms to minimise overflowing.
Increased water temperatures • Increases in temperature can influence biological systems by modifying the timing of spawning, the tolerance to increased water temperatures, the range and distribution of some species, and composition and interactions within marine communities (Walther et al. 2002). • Pond evaporation rates will be increased the increased salinity may adversely affect less salt-tolerant species. • Temperature-induced disease outbreaks may increase (Harvell et al. 2002). • Increases in air temperature may lead to a change in the geographic suitability for some pond-based systems (Voice et al. 2006).	
Changed rainfall patterns and more frequent and intense storms • Changes to rainfall patterns will lead to changes in suspended sediment and nutrient loads. • Alteration of precipitation patterns will alter salinity, nutrients and suspended sediment levels of coastal waters with implications for coastal aquaculture. The viable regions for aquaculture may shift, depending on species. • Decreased rainfall will negatively impact aquaculture industries that rely on rainfall to fill dams and ponds. • Storms may increase flood risk which in turn threaten brackish water ponds reducing farm production. Severe flooding may result in mass mortalities. • Storms may also increase the frequency of physical damage, infrastructure damage and stock losses. This may be exacerbated by rising sea level and storm surges. • Increases in nutrient pulses, algal blooms and storm surges can negatively affect profitability (NCCARF 2011b). • Severe rainfall events may result in loss of stock through potential for escape of stock (e.g. flooding of ponds).	

More Information

For more information, including projections for 2050 and 2070, please refer to http://www.climatechangeinaustralia.gov.au/en/ or McInnes et al. 2015.

For more information on the varying and changing climate please see the Queensland Government and The Long Paddock websites at http://www.qld.gov.au/environment/climate/climate-change/ and http://www.longpaddock.qld.gov.au, in particular:

- **The Climate Change Risk Management Matrix -** *http://www.longpaddock.qld.gov.au/products/matrix/index.html*
- **Queensland Coastal Hazard Area Maps -** *http://ehp.qld.gov.au/coastal/management/coastal_plan_maps.php#map_layers*

Citation
Cobon DH, Terwijn M, and Williams AAJ (2017). Impacts and adaptation strategies for a variable and changing climate in the WHITSUNDAY HINTERLAND AND MACKAY REGION. International Centre for Applied Climate Sciences, University of Southern Queensland, Toowoomba, Queensland, Australia.

Acronyms
ENSO, El Niño Southern Oscillation
GVP, Gross Value of Production
IPO, Interdecadal Pacific Oscillation
MJO, Madden Julian Oscillation or 40 day wave
PDO, Pacific Decadal Oscillation
SOI, Southern Oscillation Index
SST, Sea Surface Temperature

The authors would like to acknowledge the expertise in reviewing this document by staff in the Queensland Department of Science, Information Technology and Innovation, the Queensland Department of Agriculture and Fisheries, CSIRO, the Bureau of Sugar Experiment Stations and the Queensland Seafood Industry Association.

References

Australian Bureau of Statistics (**ABS**) 2016a, Value of agricultural commodities produced, Australia, 2014-15, Category Number: 7503.0, Australian Burean of Statistics © Commonwealth of Australia, http://www.abs.gov.au.

Australian Bureau of Statistics (**ABS**) 2016b, Agricultural Commodities, Australia, 2014-15, Category Number: 71210.0, Australian Burean of Statistics © Commonwealth of Australia, http://www.abs.gov.au

Bonanno, GA, Brewin, CR, Kaniasty, K and La Greca, AM 2010, Weighing the Costs of Disaster: Consequences, Risk, and Resilience in Individuals, Families, and Communities, Psychological Science in the Public Interest, vol. 11, pp. 1-49

Booth, D, Edgar, G, Figueria, W, Jenkins, G, Kingsford, M, Lenanton, R and Thresher, R 2009, Temperature Coastal and Demersal Fish and Climate Change, A Marine Climate Change Impacts and Adaptation Report Card for Australia 2009

Bureau of Meteorology (**BoM**) 2016, Australian climate variability and change - Trend Maps, Bureau of Meteorology, http://reg.bom.gov.au/cgi-bin/climate/change/trendmaps.cgi

Cai, W, Shi, G, Cowen, T, Bi, D and Ribbe, J 2005, The response of the Southern Annular Mode, the East Australian Current, and the southern mid-latitude ocean circulation to global warming, Geophysical Research Letters, vol. 32

Cai, W., Borlace, S., Lengaigne, M., Van Rensch, P., Collins, M., Vecchi, G., Timmermann, A., Santoso, A., McPhaden, M.J., Wu, L. and England, M.H. 2014, Increasing frequency of extreme El Niño events due to greenhouse warming. *Nature climate change*, *4*(2), pp.111-116.

Cai, W., Wang, G., Santoso, A., McPhaden, M.J., Wu, L., Jin, F.F., Timmermann, A., Collins, M., Vecchi, G., Lengaigne, M. and England, M.H. 2015. Increased frequency of extreme La Niña events under greenhouse warming. *Nature Climate Change*, *5*(2), pp.132-137.

Caldeira, K. and M. E. Wickett. 2005,"Ocean model predictions of chemistry changes from carbon dioxide emissions to the atmosphere and ocean." *Journal of Geophysical Research: Oceans* 110.C9.

Canegrowers 2011, Annual Report 2010/11, Queensland Cane Growers Organisation Ltd, Brisbane, Queensland http://www.canegrowers.com.au

Clewett, JF, Clarkson, NM, George, DA, Ooi, SH, Owens, DT, Partridge, IJ and Simpson GB 2003, Rainman StreamFlow version 4.3: a comprehensive climate and streamflow analysis package on CD to assess seasonal forecasts and mangement climate risk, QI03040, Department of Primary Industries, Queensland

Cobon, D, Stone, G, Carter, J, Scanlan, J, Toombs, N, Zhang, X, Willcocks, J and McKeon, G 2009, The Climate Change Risk Management Matrix for the grazing industry of northern Australia, The Rangeland Journal, vol. 31**,** pp.31-49 http://www.longpaddock.qld.gov.au/about/publications/index.html

Cobon, DH, Williams, AJ, Power, B, McRae, D and Davis, P 2016. Risk matrix approach useful in adapting agriculture to climate change in Central Slopes NRM New South Wales. Climatic Change 138(1), 173-189. http://dx.doi.org/10.1007/s10584-016-1732-z

Commonwealth Scientific and Industrial Research Organisation and Bureau of Meteorology (**CSIRO and BOM**) 2012, State of the Climate 2012, Commonwealth Scientific and Industrial Research Organisation and Bureau of Meteorology http://www.csiro.au/Outcomes/Climate/Understanding/State-of-the-Climate-2012.aspx

CSIRO and Bureau of Meteorology 2015, Climate Change in Australia Information for Australia's Natural Resource Management Regions: Technical Report, CSIRO and Bureau of Meteorology, Australia

Dairy Australia 2011, Climate Toolkit, Dairy Australia http://www.dairyaustralia.com.au

Dairy Australia 2015. Australian Dairy Industry in Focus, Dairy Australia Limitied 2015. 2015ISSN 2202-7467 (Online); ISSN 1448-9392 (Print).

Daly, JJ 1984, Cattle need shade trees, Queensland Agriculture Journal, vol. 110**,** pp.21-24.

Department of Climate Change and Energy Efficiency (**DCCEE**) 2011, Change Risks to Coastal Buildings and Infrastructure: A Supplement to the First Pass National Assessment, Commonwealth of Australia (Department of Climate Change and Energy Efficiency), http://www.climatechange.gov.au/~/media/publications/coastline/riskscoastalbuildings.pdf

Department of Climate Change and Energy Efficiency (**DCCEE**) 2012, Climate Change - potential impacts and costs: Queensland, Commonwealth of Australia (Department of Climate Change and Energy Efficiency), http://www.climatechange.gov.au/en/climate-change/impacts/national-impacts/~/media/publications/adaptation/fs-QLD-PDF.pdf

Department of Environment and Resource Management (**DERM**) 2012, Queensland Coastal Plan, State of Queensland (Department of Environment and Resource Management), http://www.derm.qld.gov.au/coastalplan/pdf/qcq-web.pdf

Department of Science, Information Technology, Innovation and the Arts (**DSITIA**) 2012, Queensland's Land Use Innundation of 0.8m Sea level above Highest Astronomical Tide. Base Data: Geoscience Australia 2011. 1 Second SRTM derived hydrological digital elevation model (DEM-H) Version 1.0, Canberra, Brisbane, http://ehp.qld.gov.au/coastal/management/coastal_plan_maps.php#map_layers

Deuter, P 2008, Defining the Impacts of Climate Change on Horticulture in Australia, Reports Commissioned by the Garnaut Climate Change Review, http://www.garnautreview.org.au/CA25734E0016A131/pages/all-reports--resources-commissioned-reports.html

Doherty, TJ and Clayton, S 2011, The Psychological Impacts of Global Climate Change, American Psychologist, vol. 66**,** pp. 265-76

Dryden, K 2009, Constructed wetland treating banana farm runoff, Terrain Natural Resource Management, http://www.terrain.org.au/news-for-members/547-constructed-wetland-treating-banana-farm-runoff.html

Finch, VA, Bennett, IL and Holmes, CR 1984, Coat colour in cattle - effect on thermal balance, behaviour and growth, and relationship with coat type, Journal of Agriculture Science, vol. 102**,** pp. 141-47

Fisheries Queensland 2015, Ross Lobegeiger Report to Farmers Aquaculture Production Summary for Queensland 2014-15. *Department of Agriculture and Fisheries, Queensland Government* 2015.

Fisheries Queensland 2016, Fisheries Queensland Summary Status Reports, https://www.daf.qld.gov.au/fisheries/monitoring-our-fisheries/data-reports/sustainability-reporting/queensland-fisheries-summary

Fordyce, G, Tyler, R and Anderson, VJ 1990, Effect of reproductive status, body condition and age of Bos indicus cross cows early in a drought on survival and subsequent reproductive performance, Australian Journal of Experimental Agriculture, vol. 30**,** pp. 315-22

Harvell C.D., Mitchell C.E., Ward J.R., Altizer S., Dobson A.P., Ostfeld R.S. and Samuel M.D. 2002. Climate warming and disease risks for terrestrial and marine biota. Science 296: 2158-2162.

Hobday, AJ, Poloczanska, ES and Matear, RJ (eds) 2008, Implications of Climate Change for Australian Fisheries and Aquaculture: a preliminary assessment, Report to the Department of Climate Change, Canberra.

Holbrook, N J, & Johnson, J E 2014, Climate change impacts and adaptation of commercial marine fisheries in Australia: a review of the science. *Climatic change, 124*(4), 703-715. doi:10.1007/s10584-014-1110-7.

Hopkins, PS, Knight, GI and Le Feuvre, AS 1978, Studies of the environment physiology of tropical Merinos, Australian Journal of Agricultural Research, vol. 29**,** pp. 161-71.

Horticulture for Tomorrow (**HAL**) 2012, Horticulture for Tomorrow: For Growers, Your Catchment, Queensland, http://www.horticulturefortomorrow.com.au/for_growers/your_catchments/qld.asp

Howard, WR et al. 2012, Ocean acidification, In: A Marine Climate Change Impacts and Adaptation Report Card for Australia 2012, Poloczanska, ES, Hobday, AJ and Richardson, AJ (eds.), http://www.oceanclimatechange.org.au

Howden, SM, Crimp, SJ and Stokes, CJ 2008, Climate change and Australian livestock systems: impacts research and policy issues, Australian Journal of Experimental Agriculture, vol. 48**,** pp.780-88

Howden, SM, Hall, WB and Bruget, D 1999, Heat stress and beef cattle in Australian rangelands: recent trends and climate change, People and Rangelands, Building the Future, Proceedings of the 6th International Rangelands Conference**,** pp. 43-44

Hughes, L and McMichael, T 2011, The Critical Decade: Climate change and health, Climate Commission, Commonwealth of Australia (Department of Climate Change and Energy Efficiency), http://climatecommission.gov.au/wp-content/uploads/111129_FINAL-FOR-WEB.pef

Hunt, J 2011, Media Release: 12 September 2011: 2010's soggy legacy causing issues for cane growers as harvest reaches half-way, Cane Growers Association, http://www.canegrowers.com.au/page/Industry_Centre/Media_Centre/media-releases-archive/Media_Releases_2011/2010s_soggy_legacy_causing_issues_for_cane_growers_as_harvest_reaches_half-way/

Intergovernmental Panel on Climate Change (**IPCC**) 2013, **Scenario Process For Ar5**, http://sedac.ipcc-data.org/ddc/ar5_scenario_process/index.html.

Jackson, CJ, and Wang, Y-G, 1998, Modelling growth rate of *Penaeus monodon* Fabricus in intensively managed ponds: effects of temperature, pond age and stocking density. Aquaculture Research, 29: 27-36.

Jackson CJ, Preston NP, Burford MA and Thompson P 2003. Managing the development of sustainable shrimp farming in Australia: the role of sedimentation ponds in treatment of farm discharge water. Aquaculture 226: 23-34.

Johnson, JE and Marshall, PA 2007, Climate Change and the Great Barrier Reef, Great Barrier Reef Marine Park Authority and Australian Greenhouse Office

King, JM 1983, Livestock water needs in pastoral Africa in relation to climate and forage, Addis Ababa, ILCA Research report**,** vol. 94.

Langston, J, and Turton, SM 2014, *Industry-adaptation pathways and opportunities in the Wet Tropics cluster.* In: Moran, C, Turton, S M., and Hill, R, (eds.) Adaptation Pathways and Opportunities for the Wet Tropics NRM Cluster Region: volume 2: infrastructure, industry, indigenous peoples, social adaptation, emerging planning frameworks, evolving methodologies and climate adaptation planning in practice. James Cook University, Cairns, QLD, Australia, pp. 128-143.

Leslie, LM, Karoly, DJ, Leplastrier, M and Buckley, BW 2007, Variability of Tropical Cyclones over the Southwest Pacific Ocean using High Resolution Climate Model, Meteorology and Physics, vol. 97 (Special Issue on Tropical Cyclones)

Low, T 2011, Climate Change and Terrestrial Biodiversity in Queensland, Department of Environment and Resource Management, Queensland Government, Brisbane.

McInnes, K. *et al.,* 2015, *Wet Tropics Cluster Report*, Climate Change in Australia Projections for Australia's Natural Resource Management Regions: Cluster Reports, eds. Ekström, M. *et al.*, CSIRO and Bureau of Meteorology, Australia.

Marshall, NA,2014. Social adaptation: minimising impacts through enhancing adaptive capacity. In: Moran, C, Turton, S M., and Hill, R, (eds.) Adaptation Pathways and Opportunities for the Wet Tropics NRM Cluster Region: volume 2: infrastructure, industry, indigenous peoples, social adaptation, emerging planning frameworks, evolving methodologies and climate adaptation planning in practice. James Cook University, Cairns, QLD, Australia, pp. 168-178.

Marshall, NA, Capon, S, Curnock, M, Edgar, B, Race, D & Scherl, LM 2015, A handbook for enhancing social resilience in the Monsoonal North of Australia. CSIRO Land and Water, Townsville.

McKeon, G, Hall, W, Henry, B, Stone, G and Watson, I 2004, Learning from history. Pasture degradation and recovery in Australia's rangelands, Queensland Department of Natural Resources, Mines and Energy, Brisbane

McKeon, GM, Stone, GS, Syktus, JI, Carter, JO, Flood, NR, Ahrens, DG, Bruget, DN, Chilcott, CR, Cobon, DH, Cowley, RA, Crimp, SJ, Fraser, GW, Howden, SM, Johnston, PW, Ryan, JG, Stokes, CJ and Day, KA 2009, Climate change impacts on northern Australian rangeland livestock carrying capacity: a review of issues, A Climate of Change in Australian Rangelands, The Rangeland Journal, vol. 31**,** pp.1-30

Meat and Livestock Australia (**MLA**) 2010, Cattle numbers - as at June 2010: Natural Resource Management Region, Meat and Livestock Australia, http://www.mla.com.au/About-the-red-meat-industry/Industry-overview/Cattle

Mott, JJ and Edwards, GP 1992, Beyond beef - a search for a level grazing paddock, Search, vol.7, pp. 223-5

Munday, P.L., Jones, G.P., Pratchett, M.S., Williams A.J. 2008. Climate Change and the Future for Coral Reef Fishes. *Fish and Fisheries* **9**, 261-285.

Murphy, R and Simpson, G 2011, Balancing dairy production and profits in Northern Australia: QDAS Financial and production trends – 2011, Department of Employment, Economic Development and Innovation, Toowoomba, Queensland

National Climate Change Adaptation Research Facility (**NCCARF**) 2011a, Climate change impacts factsheet: 8. Human Health, http://www.nccarf.edu.au/sites/default/files/8.Health-Impacts.pdf

National Climate Change Adaptation Research Facility (**NCCARF**) 2011b, Climate change impacts factsheet: 4. Primary Industries, http://www.nccarf.edu.au/sites/default/files/4.Primary-Industries-Impacts.pdf

National Climate Change Adaptation Research Facility (**NCCARF**) 2011c, Climate change impacts factsheet: 1. Marine biodiversity and resources, http://www.nccarf.edu.au/sites/default/files/1.Marine-Impacts.pdf

Nowak, RS, Ellsworth, DS and Smith, DS 2004, Functional responses of plants to elevated atmospheric CO_2 - do photosynthetic and productivity data from FACE experiments support early predictions? New Phytologist, vol. 162**,** pp. 253-80

Poloczanska, ES, Hobday, AJ and Richardson, AJ 2009, Report Card of Marine Climate Change for Australia, In: Poloczanska, ES, Hobday, AJ and Richardson, AJ (eds.), NCCARF Publication 05/09

Potgieter, A, Meinke, H and Doherty, A 2004, Likely impact of climate on wheat and sorghum production in central Queensland, 4th International Crop Science Congress, Brisbane

Queensland Department of Agriculture, Fisheries and Forestry (**QLDDAFF**) 2010, Sugar, http://www.daff.qld.gov.au/26_6730.htm

Queensland Farmer's Federation (**QFF**) 2012, Farming in Queensland, Queensland Farmer's Federation, http://www.qff.org.au/farming-in-qld/

Reef Catchments 2010, Reef Rescue 2010: Wet Season Cover Crop, Reef Catchments, www.reefcatchments.com.au

Reside, AE, Ceccarelli, DM, Isaac, JL, Hilbert, DW, Moran, C, Llewelyn, J, Macdonald, S, Hoskin, CJ, Pert, P, and Parsons, J 2014 *Biodiversity: adaptation pathways and opportunities.* In: Moran, C, Turton, S M., and Hill, R, (eds.) Adaptation Pathways and Opportunities for the Wet Tropics NRM Cluster Region: volume 1: introduction, biodiversity and ecosystem services. James Cook University, Cairns, QLD, Australia, pp. 11-74.

Scientific Advisory Group (**SAG**) 2010, Increasing Queensland's resilience to inland flooding in a changing climate, Final Scientific Advisory Group report, Department of Environment and Resource Management, Brisbane, http://www.ehp.qld.gov.au/climatechange/pdf/inland-flood-study.pdf

Rossiter NA, Douglas MM, Setterfield SA and HutleyLB 2003. Testing the Grass-Fire Cycle: Alien Grass Invasion in the Tropical Savannas of Northern Australia. *Diversity and Distributions* 9: 169-176.

Standards Australia 2004, AS/NZS4360:2004 Risk Management

Stokes, C 2011, Developing improved industry strategies and policies to assist beef enterprises across northern Australia adapt to a changing and more variable climate, MLA Milestone 3 report, Project No. B.NBP.0617, Meat and Livestock Australia

Stokes, C and Howden, M 2010, Adapting agriculture to climate change: preparing Australian agriculture, forestry and fisheries for the future, CSIRO

Stokes, C, Ash, AJ, Scanlan, J and Webb, N 2011, Strategies for adapting to climate change, Proceedings of the Northern Beef Research Conference, Darwin**,** pp. 81-86

Stokes, CJ, Ash, AJ and Holtum, JA 2008, Savannas face the future: windows into a future CO_2 enriched world, A Climate of Change in the Rangelands, 15th Biennial Conference, Charters Towers, Queensland, Australian Rangeland Society

Sun, C, Feng, M, Matear, RJ, Chamberlain, MA, Craig, P, Ridgeway, KR and Schiller, A 2011, Marine downscaling of a future climate scenario for Australian boundary currents, Journal of Climate, In Press.

Sutherst, RW 1990, Impact of climate change on pests and diseases in Australia, Search, vol. 21**,** pp. 232

The Climate Institute (**TCI**) 2011, A Climate of Suffering: the real cost of living with inaction on climate change (Melbourne and Sydney), The Climate Institute

Tothill, CJ and Gillies, C 1992, The pasture lands of northern Australia - their condition, productivity and sustainability, Tropical Grassland Society of Australia, Occasional Publication No 5, Brisbane

Voice, M, Harvey, N and Walsh, K 2006, Vulnerability to Climate Change of Australia's Coastal Zone: Analysis of gaps in methods, data and system thresholds, Report to the Australian Greenhouse Office, Canberra

Walsh, KJE, Nguyen, KC and McGregor, JL 2004, Finer resolution regional climate model simulations of the impact of climate change on tropical cyclones near Australia, Climate Dynamics, vol. 22

Walther, G, Post, E, Convey, P, Menzel, A, Parmesan, C, Beebee, TJC, Hoegh-Guldberg, O and Bairlein, F 2002, Ecological responses to recent climate change, Nature, vol. 146**,** pp. 389-95

Webb, NP, Stokes, CJ and Scanlan, JC 2011, Interacting effects of vegetation, soils and managment on the sensitivity of Australian savanna rangelands to climate change, Climate Change, DOI: 10.1007/s10584-011-0236-0

White, N, Sutherst, R, Hall, W and Whish-Wilson, P 2003, The vulnerability of the Australian beef industry to the impacts of the cattle tick (Boophilus microplus) under climate change, Climatic Change, vol. 61**,** pp. 157-90

Witte, C, van den Berg, D, Rowland, T, O'Donnell, T, Denham, R, Pitt, G and Simpson, J 2006, Mapping Land Use in Queensland - Technical Report on the 1999 Land Use Map for Queensland, NRMW, Brisbane.

Williams KJ, Prober SM, Harwood TD, Doerr VAJ, Jeanneret T, Manion G, and Ferrier S (2014) Implications of climate change for biodiversity: a community-level modelling approach, CSIRO Land and Water Flagship, Canberra. Available at:***www.AdaptNRM.org*** ISBN 978-1-4863-0479-0.