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Climate Change -Risks and Opportunities for the Avocado Industry

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SUMMARY

Climate affects the avocado industry in a range of ways through impacts on growth, disease risk, fruit quality and industry location.

Climates in Australia and New Zealand are influenced by surrounding oceans, and are very variable from year to year. However, amidst this variability there are significant trends, with Australian annual mean temperatures increasing since 1910, and particularly since 1950. Night-time temperatures have increased faster (0.11^{o}C/decade) than daytime temperatures (0.06^{o}C/decade). These temperature increases and other climate changes are expected to continue as a result of greenhouse gas emissions, with ongoing impacts on the avocado industry.

Eight sites were chosen to assess possible future climate changes : Mareeba, Bundaberg, Nambour, Gatton, Toowoomba, Coffs Harbour, Mildura and Manjimup, these sites representing important avocado production regions in Australia. A mean warming of 0.4 to 2.0^{o}C is anticipated over most of these sites by the year 2030, relative to 1990, and 1 to 6^{o}C by 2070. New Zealand, with more temperate environments and being smaller and more mountainous, may not be as vulnerable to climate change as is Australia, which has most of its landmass in the tropics and subtropics.

This paper assesses the potential effects of climate change on avocado production, and suggests strategies for adaptation.

KEY WORDS: avocado, climate change scenarios, climate variability, adaptation strategies, greenhouse gasses, atmospheric CO_2 enrichment, climate model simulations, climate change impacts, management options, seasonal climate forecasting

INTRODUCTION

The avocado industry is affected in a range of ways by climate since it affects growth, disease risk, fruit quality and industry location (see Table 1). Amongst many other considerations, management and infrastructure decisions attempt to account for these climate effects and risks. Such decisions will usually use the historical climate as a guide to future conditions.

There is increasing evidence that human activities are already changing the global climate, and that more change seems likely. Consequently, historical conditions may become increasingly less pertinent as a guide to industry activities or industry adjustment. This paper assesses the evidence for climate change, drawing particularly on the IPCC Third Assessment Report (IPCC 2001a, b, 2002), and explores the potential impacts and implications of such changes for the avocado industry in Australia.

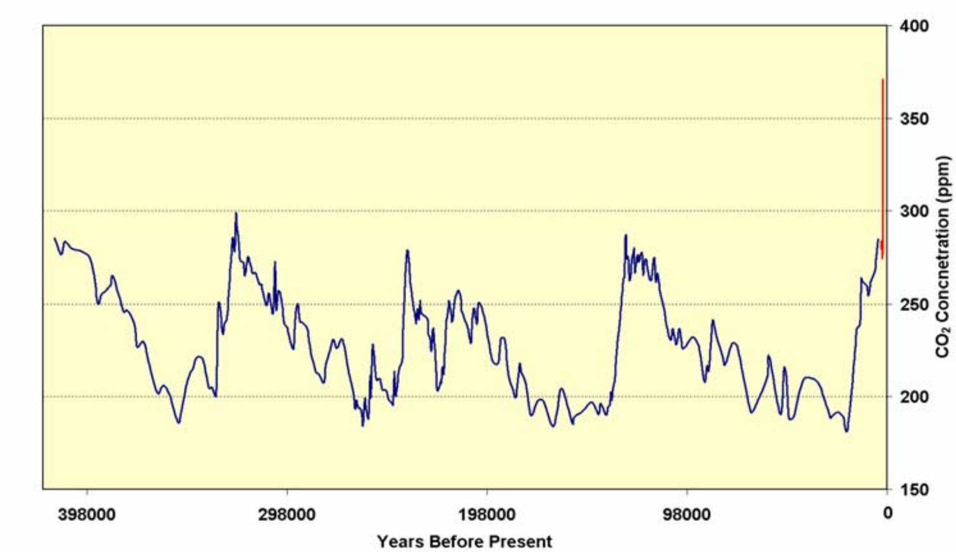

Fig 1 Changes in atmospheric CO_2 concentration (Petit *et al*., 2000)

WHAT IS CHANGING, AND BY HOW MUCH?

Recent changes

It is certain that the atmospheric concentration of various gases and particulates has changed over the past century, and there is much evidence that they are now higher than at any time in the past 420,000 years (Petit et al., 2000). The concentration of these atmospheric constituents has consequences for the absorption of solar radiation by the atmosphere, and thus global and regional climates. In the case of the main 'greenhouse gases', notably carbon dioxide (CO_2) (Fig 1), methane (CH_4) and nitrous oxide (N_2O), the sign, magnitude and longevity of this effect is well-established; and the increased concentrations of these gases results in a net warming of the globe (IPCC, 2000, 2001a). In the case of the minor or more transient gases (such as the tropospheric ozone-precursors), the effect is known to be warming, but the degree, duration and distribution of the warming around the planet is less certain. For particulates, the direct effect can either be warming (for dark, highly absorptive particles such as soot) or cooling (for reflective particles such as sulphate), and their impact depends partly on their location in the atmosphere (IPCC, 2001a). Particulates can cause or prevent the formation of clouds, which in turn either cool or warm the earth, depending on their type and location. Thus, the net effect of particulates remains uncertain in both sign and magnitude. Nevertheless, independent evidence from observations of the climate of the past century and a half, strongly implies that the total global radiant energy (gases and particulates) is having a warming effect on the world.

Table 1. How climate affects critical stages in avocado production.

Climatic factor	**Impact on avocado growth and development**
Storm damage (incl. cyclones)	Fruit loss, tree and infrastructure damage
Frost when flower buds, flowers or freshly set fruit are present	Frost affects flower buds, flowers and small fruit, thus reducing crop yield
Cold weather during flowering, fruitset and during the first few weeks after fruitset	Night temperatures of 10 to 15oC or lower, for extended periods during flowering and for a few weeks after flowering can reduce pollination, fruit set and fruit retention
Very low humidity and high winds at flowering	Desiccation of flowers and fruitset failure
Heat stress and high solar radiation	Sunburn damage to fruit and exposed branches Research in some horticultural crops suggests enhanced radiation increases fruit and tree susceptibility to pathogens
High summer temperatures	Smaller sized 'Hass' fruit
Higher maximum and minimum temperatures	Earlier maturity under higher temperature conditions and vice versa
Diurnal temperature variation	The greater the diurnal temperature range the greater the chances for male and female flower parts being open at the same time, and therefore achieving pollination and fruit set
Periods of warm weather and high rainfall leading to soil saturation	Increased incidence and severity of *Phytophthora cinnamomi*
Wet conditions for 48 hours or longer	Fruit can become infected by anthracnose and other fruit rot diseases (e.g. stem end rot) if fruit are wet for 48 hours or more. Stress during fruit development appears to make them more susceptible to these diseases
Warm season, especially when combined with high humidity	Increased incidence of insect pests, eg. fruit spotting bug and *Monolepta sp.*
Hot sites and hot windy conditions	Higher evaporation rates and thus greater need for irrigation and mulch
Combination of suitable soils and climate	Industry location

It is very likely that the global mean atmospheric temperature near the earth's surface has risen by 0.73ºC since 1850 when measurements began, and is now higher than at any time during at least the past thousand years. About three-quarters of the change observed since 1850 is attributed to human actions (IPCC, 2001a).

Australian annual mean temperatures have increased by 0.82^{o}C since 1910, with rapid increases, particularly since 1950 (Smith, 2004), with night-time temperatures increasing faster (0.11^{o}C/decade) than daytime temperatures (0.06^{o}C/decade). Night-time (minimum) temperatures have particularly risen sharply in the northeast of Australia. There are also trends from 1957 to 2003 of increasing frequency in hot days (35^{o}C or more) of 0.08 days per year and a decreasing trend in cold nights (5^{o}C or less) of 0.16 nights per year (Hennessy *et al*., 2004a).

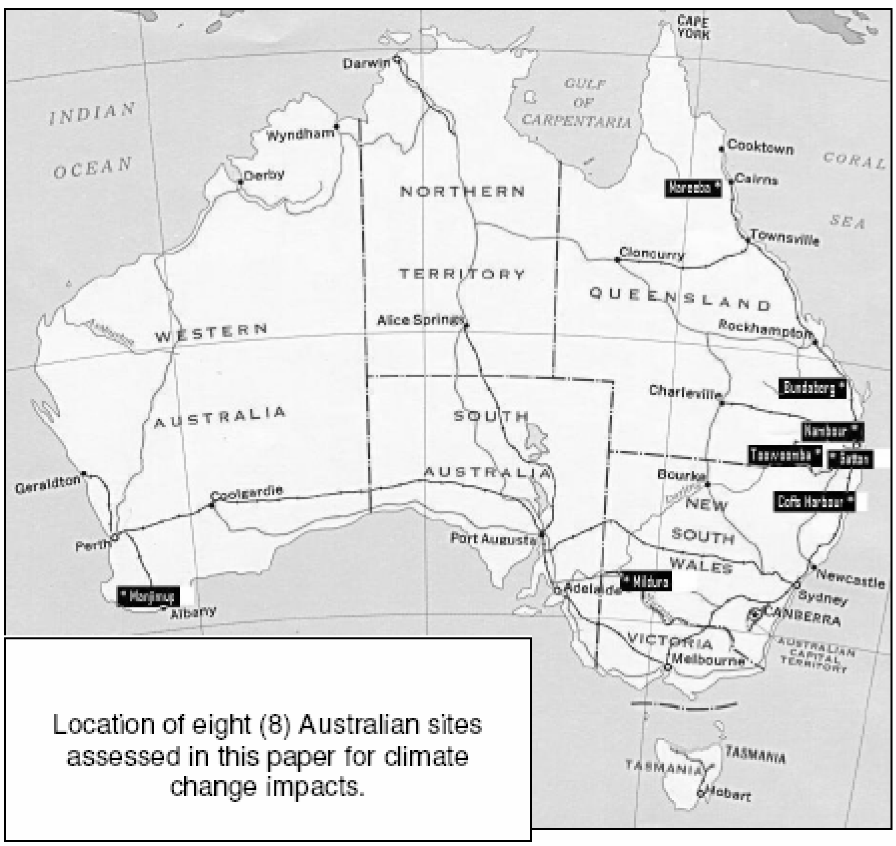

Fig 2 Eight sites assessed for climate change impacts.

Since 1900, annual Australian-average rainfall shows a moderate increase (7.9mm/decade), but it is dominated by high year-to-year variability (Smith, 2004). While north-eastern Australia has become wetter since 1950, much of eastern and southern Australia has become drier. This is due to a weakening or southward shift of the frontal systems that bring most rain to these regions (Marshall, 2003) and generally wetter conditions during the 1950's. Rainfall intensity in eastern Australia has increased from

1910 to 1998, but has decreased in the far southwest of Australia (Haylock and Nicholls, 2000) over this same time period. Over New South Wales, extreme daily rainfall intensity and frequency has decreased from 1950 to 2003 (Hennessy *et al*., 2004b).

The frequency of tropical cyclones in the Australian region has decreased since 1967 (Hennessy, 2004c), along with an increase in cyclone intensity, possibly as a result of a shift in areas of formation. Explosively developing cyclones, including East Coast Lows off the New South Wales coast, have increased between 1979 and 1999 (Lim and Simmonds, 2002).

There have also been climate changes in regions where the avocado industry is strongly represented. We have selected eight sites (Fig 2) to assess such changes: Mareeba, Bundaberg, Nambour, Gatton, Toowoomba, Coffs Harbour, Mildura and Manjimup, these sites representing important avocado production regions in Australia.

Table 2. Historical temperature changes (1957 to 2005) with temperature trends expressed in degrees Celsius per 100 years, calculated using linear regression, for eight locations in Australia.

Site	Annual mean temperature change	Annual dewpoint temperature change	Winter minima change	Summer maxima change
Mareeba	2.52	1.34	5.3	0.9
Bundaberg	1.70	1.75	2.2	1.0
Nambour	3.26	1.72	6.1	1.1
Gatton	1.97	1.32	1.5	2.9
Toowoomba	1.46	0.64	2.7	1.3
Coffs Harbour	1.93	0.14	3.4	0.9
Mildura	0.49	-0.77	-0.1	1.6
Manjimup	1.14	1.82	1.4	0.9

Temperature affects avocados in many ways, including influencing timing and reliability of flowering, fruit growth, ripening and fruit quality. There are strong trends of increased mean annual temperature across the eight sites (Table 2), ranging from 0.49^{o}C per century (Mildura) to 3.26^{o}C per century (Nambour) with an average of 1.8^{o}C. About 60 to 80% of the warming arises from change in night-time temperatures (except for Mildura where all the warming is from daytime temperatures) and 55 to 70% of the warming is from temperature increases in the May-October period (again with the exception of Mildura which is 35%).

There were weak trends of declining rainfall in most sites and most seasons, however, these were mostly not statistically significant, with the exception of Bundaberg where rainfall during November to May showed significant declines (Fig 3). These apparent declines may in part have been the result of a period of above average rainfall experienced in the late 1950’s.

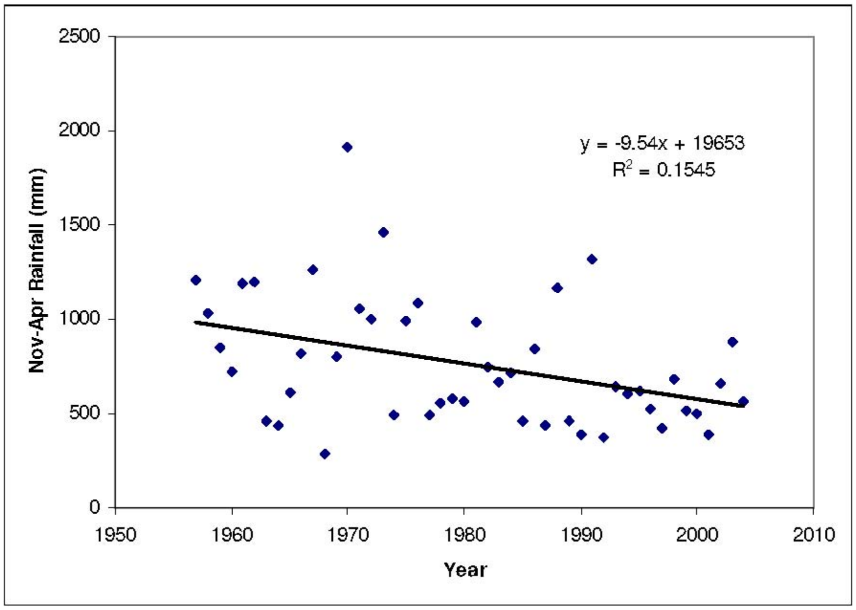

Fig 3 November to April rainfall (mm) from 1957 to 2005 for Bundaberg.

Table 3. Changes in the numbers of frosts, the timing of the first and last frosts and the length of the frost period in frost affected sites (over the past 50 years).

Site	Change in the number of frosts	Change in the timing of the first frost	Change in the timing of the last frost	Change in the length of the frost period
Nambour	-14	39	-43	-81
Gatton	-9	12	-19	-31
Toowoomba	-15	26	-14	-40
Coffs Harbour	-6	27	-16	-43
Manjimup	-4	15	-43	-58

Note: No significant changes in frost incidence have occurred in Mildura. Mareeba and Bundaberg are generally not frost-affected. Frost trends for Toowoomba and Gatton have had the trend component from rainfall changes removed.

Fruit set in avocado is sensitive to late frosts during spring. In frost-affected avocado-growing regions in Australia, there have been significant decreases over the past five decades in the number of frosts (Table 3), the date of last frost, the length of the frost period and the date of the first frost (i.e. the first frost is slightly later -see Fig. 4). These changes are largely explained by the general increases in minimum temperatures experienced at these sites, although at some sites, increases in atmospheric humidity (see dewpoint temperatures in Table 2) and variations in rainfall also play a role. If minimum temperatures increase as projected, and providing rainfall doesn't decrease too markedly, then the historical trends towards lowered risk of frost are likely to continue.

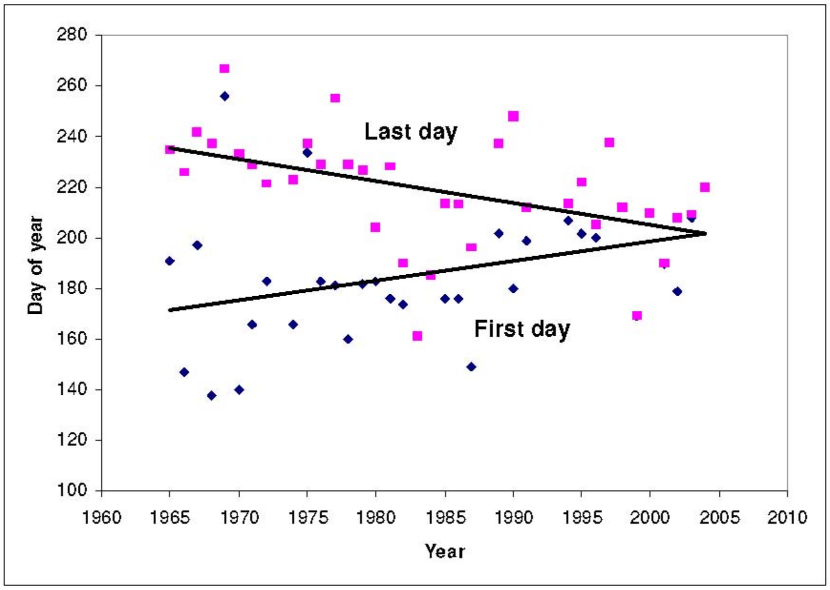

Fig 4 Trends in frost incidence for Nambour.

Anthracnose post-harvest fruit rot and insect pest attacks are favoured by warm and humid conditions. As noted above, avocado production regions are becoming warmer but there is also a general increase in atmospheric water vapour content (humidity) as measured by dewpoint temperature (Table 2).

Periods of heat stress (for example -days with temperatures above 35^{o}C) can adversely affect fruit set and fruit size. Fruit can also be burnt by high radiation loads. Generally across the eight sites, there are trends towards increasing numbers of heat stress days and higher radiation loads (Table 4).

Table 4 Historical changes in evaporation (mm), diurnal temperature range (^{o}C), heat stress frequency (days per year with maximum temperature greater than 35^{o}C) and radiation (MJ/m^{2}) for eight sites in Australia (1957 to 2005), with trends expressed as a change per 100 years.

Site	Daily evaporation change	Change in diurnal temperature range	Change in heat stress frequency	Radiation change
Mareeba	0.28	-3.1	1.05	-0.24
Bundaberg	0.16	-0.25	1.29	0.44
Nambour	0.44	-2.76	2.79	-0.01
Gatton	0.55	2.51	14.33	1.14
Toowoomba	0.46	-0.37	-0.33	1.97
Coffs Harbour	0.62	-1.04	0.72	2.12
Mildura	0.32	1.50	7.88	1.20
Manjimup	0.08	-0.28	-1.83	1.42

Fruit set is also enhanced by high diurnal temperature ranges (the difference between daytime maxima and night-time minima); this too has been decreasing in most of the eight sites over the past 48 years (Table 4). A low diurnal temperature range decreases the chances of male and female flower parts being open at the same time to achieve pollination.

Irrigation demand is strongly affected by evaporation rates. High quality, long-term and consistent measurements of evaporation are rare. We have used the Penman-Monteith equation (FAO) to estimate potential evaporation based on more commonly measured atmospheric variables. However, wind-run is not varied and where this has changed, we will not have represented this in our estimates which show increases in potential evaporation across all sites (Table 4). This is likely to have resulted in progressively higher irrigation requirements over time, assuming that all other factors (e.g. technology, pricing, availability) were not changed.

Projections of future change

A selection of climate models, driven by a range of scenarios of human development, technology and environmental governance, project the global mean temperature to rise a further 2 to 5.8ºC during the 21st Century (IPCC, 2000). This is a large range, with about half of the variation in projected temperatures being due to uncertainties in the climate models, and the other half due to uncertainties regarding greenhouse gas emissions which are closely tied to social, economic and technological aspects of our future. The projected warming is not evenly distributed around the globe: continental areas warm more than the ocean and coastal areas, and the poles warm faster than equatorial areas. When translated to Australia, there are anticipated to be substantial increases in temperature over and above those already experienced.

For the eight avocado growing sites assessed, expected changes by 2030 are about 0.3 to 1.7°C, with much greater changes by 2070 (Table 5). The changes up to 2030 are consistent with the existing trends in mean temperature with extrapolations of current trends in all cases intercepting with the range of temperatures expected in 2030 (Fig. 5).

Table 5. Historical mean temperature increases (°C) for the eight avocado growing sites compared with scenarios of temperature change from the 1960 to 1990 baseline period.

Site	Temperature increase (°C /100 yrs)	Scenario temperature increases (°C)
Mareeba	2.52	0.3 to 1.7 °C by 2030 and 1 to 6 °C by 2070
Bundaberg	1.70	0.3 to 1.7 °C by 2030 and 1 to 6 °C by 2070
Nambour	3.26	0.3 to 1.7 °C by 2030 and 1 to 6 °C by 2070
Gatton	1.97	0.3 to 1.7 °C by 2030 and 1 to 6 °C by 2070
Toowoomba	1.46	0.3 to 1.7 °C by 2030 and 1 to 6 °C by 2070
Coffs Harbour	1.93	0.2 to 1.6 °C by 2030 and 0.7 to 4.8 °C by 2070
Mildura	0.49	0.2 to 1.8 °C by 2030 and 0.7 to 5.5 °C by 2070
Manjimup	1.14	0.2 to 1.6 °C by 2030 and 0.8 to 5.2 °C by 2070

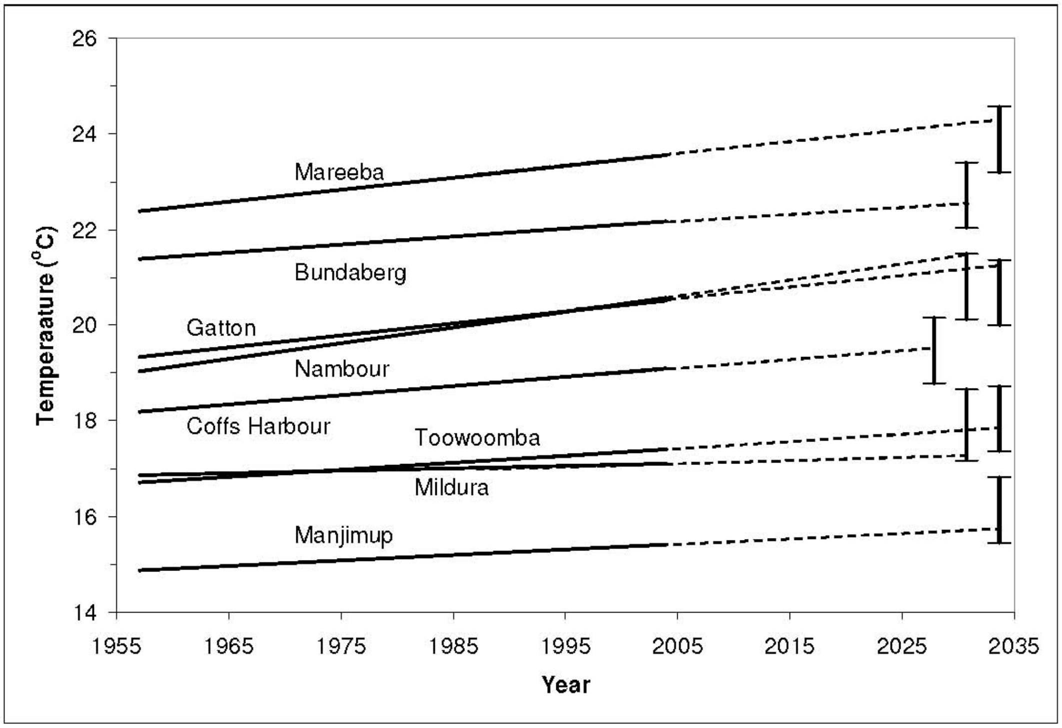

Fig. 5 Historical trends in mean annual temperature for the eight avocado growing sites (solid lines), extrapolated to year 2030 (dashed lines). The vertical bars represent the scenarios of temperature change for each site (Table 5) added to the mean temperature of the baseline period 1960 to 1990.

A ***mean warming*** of 0.4 to 2.0^{o}C is anticipated over most of Australia by the year 2030, relative to 1990, and 1 to 6^{o}C by 2070 (CSIRO, 2001) -see Table 5. Mean temperature change is likely to be greatest inland and least on the coast. Most warming is expected to occur in spring and summer, and least in winter. There is no strong indication whether the ***diurnal temperature range*** is likely to change. In contrast, the current trend towards lower ***frost risk*** is likely to continue in all frost-affected sites. However, whilst there is an expectation of a 10 to 50% increase in ***days over 35^{o}C*** by 2030, the occurrence of hot spells is more likely to increase in frequency in inland growing areas (e.g. Mildura) and to a lesser extent on the coast.

A tendency for less ***rainfall*** is expected in the south-west of WA (-20 to +5% by 2030, -60 to +10% by 2070). In much of eastern Australia, projected ranges are uncertain (e.g. -10 to +10% by 2030 and -35 to +35% by 2070). Recent analyses indicate that Queensland coastal rainfall may on balance decline but that this may vary with season. When broken down by seasons, spring rainfall tends towards decreases ranging from zero to -20% by 2030 and zero to -60% by 2070. Autumn shows a tendency for decreases with changes from +7% to -13% by 2030 and +20% to -40% by 2070. Summer (+7% by 2030 and +20% by 2070) and winter (+13% by 2030 and +40% by 2070) showing no particular directional changes (Cai et al. 2003).

There is uncertainty as to the likely change in the frequency and strength of ***El Niño***

(ENSO) events. Even in the absence of increases in El Nino events, projected changes in atmospheric moisture balance (rainfall minus potential evaporation) will lead to drier conditions over Eastern and Southern Australia and Eastern New Zealand, with a greater likelihood of droughts. These more frequent droughts are likely to be accompanied by higher temperatures, which will compound the problem. This, combined with expectations of increased evaporation, suggest increased irrigation demands.

Rainfall intensity is expected to generally increase with warmer temperatures, as the air can hold more moisture (about 6 to 8% per ^{o}C) enabling more intense precipitation. If rainfall intensity does increase, this may increase soil erosion risk and also may increase the frequency of waterlogging: conditions where *Phytophthora cinnamomi* is problematic. Scenarios of rainfall intensity (e.g. Hennessy, 2004c) indicate considerable geographical diversity in possible responses, with a tendency for a decrease in rainfall extremes along the east coast in autumn and winter, although most models project an increase in the intensity of extreme rainfall in spring and summer on the north-east coast. The projections for the Sunraysia/Riverland region were similar to the east coast. In contrast with the consistency between historical temperature trends and projected temperature changes, historical trends in rainfall intensity at the eight sites in avocado-growing regions show generally consistent decreases.

Australian ***tropical cyclone*** frequency and regions of occurrence show little change under enhanced greenhouse conditions, but there is a 56% increase in the number of ***storms*** with wind speeds exceeding 30 ms^{-1} (108 km per hr) and an increase in the number of storms south of latitude 30^{o}S (Walsh *et al*., 2004). However, the confidence in these projections is only moderate due to issues with representation of ENSO in the models.

Climate change may bring slightly higher extreme ***wind speeds*** to Mildura, especially in spring and summer, but lower wind speeds on the north coast of NSW and the Queensland coast, with exceptions under cyclonic conditions.

HOW WILL CLIMATE CHANGE AFFECT THE AUSTRALIAN AVOCADO INDUSTRY?

Climate change could feasibly affect the avocado industry in many ways. Potential effects of the climate changes outlined above are briefly documented, based on current understanding of avocado physiology.

Table 6 Climate change impacts on avocado growth and development.

Change Issues		Potential impacts on avocado growth and development
Temp. related	Less diurnal temperature range	Reduced chances of overlap between open stages of male and female flower parts. Therefore less potential for pollination and fruitset, especially in single variety plantings.
	Warmer nights	Less chance for fruitset failure in areas that currently experience crop failures due to cold nights during flowering.

		eg. 'Hass' on the Toowoomba range.
	Hotter summer temperatures	Smaller 'Hass' fruit.
	Significantly warmer autumn and winter temperatures	Potential for less flower initiation in the subtropical avocado varieties grown in warmer districts (see also below).
	Significantly warmer temperatures in general	A shift in the growing regions -away from the hotter producing areas to new areas currently regarded as being marginally too cool. A parallel scenario is provided by Houerou (1992) in a study conducted for the northern basin of Euro-Mediterranean countries which predicts that the areas of tropical and sub-tropical crops (such as citrus, sugarcane, avocados and bananas) would expand, whilst cereal cultivation would be eliminated from 8-10 million ha. This also suggests likely changes in the countries that can produce and export avocados in competition with Australia.
	Time to reach maturity	Warmer temperatures suggest that fruit will set and reach maturity earlier in the season, shifting the harvest times for different areas.
	On-tree fruit 'storage'	Warmer temperatures may reduce the period that fruit can be 'stored' on the tree and retain acceptable fruit quality.
	Phytophthora cinnamomi activity	Since the optimum soil temperature for *Phytophthora cinnamomi* is 19 to 25ºC and no infection takes place below 15ºC (K. Pegg, Brisbane, 2005, personal communication), a general rise in temperature means that the disease could be active for longer periods during the year (provided soil moisture is adequate).
	Insect activity	Insect activity is closely related to temperature, so a rise in temperature suggests more active insect populations (both pests and predators).
	Increasing number of heat stress days	Greater potential for sunburn on fruit and exposed branches. Pollination failures if heat stress days occur during flowering (Gafni, 1984) (see also below). Lower fruit retention if heat stress occurs within a few weeks of fruit set.
Moisture related	Greater moisture extremes -more frequent excessively wet and dry periods.	Increased risk of spread and proliferation of *Phytophthora cinnamomi* as a result of more frequent and intense rainfall events (coupled with warmer temperatures). Greater variation in the incidence of anthracnose infections from season to season. 'Hass' fruit size reduced by drought induced stress. Increased irrigation demand during dry spells.
Carbon dioxide	Higher levels of atmospheric carbon dioxide	Greater potential for fruit set and fruit retention (Schaffer and Whiley, 2002) -(see also below).

Heat stress

We assessed the potential change in frequency of heat stress conditions using scenarios of future temperature change in conjunction with flowering periods, drawn from Newett *et al* (2003), for each of the eight sites. Generally, the frequency of heat stress days is likely to increase only marginally if temperature increases by 2030 are at the lower end of the projection range, but increase by two to five-fold if temperature increases are at the upper end of the range. The increase in heat stress frequency with temperature is essentially exponential (Fig 6). If temperature increases proceed as indicated in the climate change scenarios, heat stress days would be commonplace during flowering at all of the eight sites, by 2030. Where there is an increase in the number of days with temperatures above 35°C during flowering, fruit development and on-tree fruit 'storage' are affected, and reduced fruit set and damage to fruit will also occur.

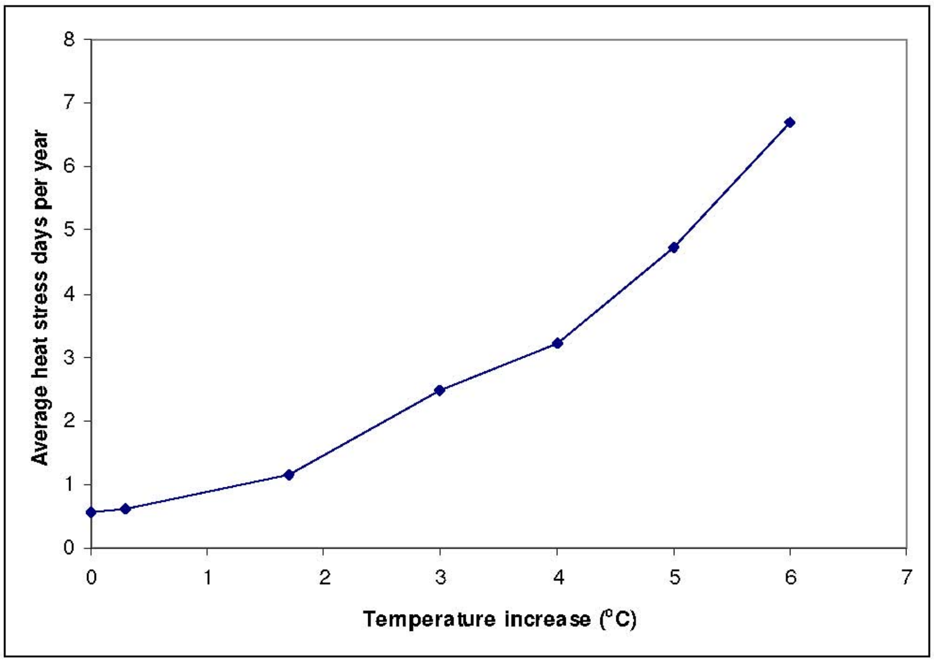

Fig. 6 Frequency of heat stress days during flowering at Gatton (Qld) for temperature increases of 0 to 6°C.

Flower initiation

Temperature is the main factor responsible for the change from the vegetative to the reproductive phase of avocados; subtropical avocado cultivars can only produce flower buds if kept under a cool temperature regime. Research showed that 'Hass' did not flower at 30/25, 25/20 or 24/19°C day/night temperatures but flowered when kept for 3-4 months at 15/10, 18/15, 20/15 and 23/18°C. Under the last two regimes, flowering was delayed and its rate was much lower. For 'Hass', the 23/18°C regime is probably close to the critical point for flowering (Gazit and Degani, 2002).

Carbon dioxide (CO_2) concentration

The effects of short-term atmospheric CO_2 enrichment (150 to 2000 µmol CO_2 mol^{-1}) on photosynthesis of 'Hass' avocado are reported in Schaffer and Whiley (2002). It was found that net CO_2 assimilation measured in leaves increased as the atmospheric CO_2

concentration increased. Witjaksono *et al* (1999) report that better shoot growth and greater biomass accumulation occurred in a CO_2-enriched environment than under ambient CO_2 conditions.

Dry matter partitioning in 'Hass' avocado trees grown at both 350 and 600 µmol CO_2 mol^{-1} is reported in Schaffer and Whiley (2002). There was a greater allocation of dry matter to the trunks of avocado trees growing at 600 µmol CO_2 mol^{-1} compared with trees at 350 µmol CO_2 mol^{-1} (Fig 7). Janse van Vuuren *et al* (1997) showed that the bulk of tree carbohydrate reserves in avocado are found in the roots and wood, and that low starch reserves at the beginning of a new reproductive season facilitate an off-year for yield. They state that for the producer it is important to promote the build up of reserves.

Research (Schaffer and Whiley, 2002) showed that by 45 days after flowering, trees grown at 600 µmol CO_2 mol^{-1} held more fruit than those at 350 µmol CO_2 mol^{-1}. Since there is a direct relationship between fruit retained at 40-50 days after flowering and final yield, it is likely that increased atmospheric CO_2 concentrations will benefit productivity of avocado.

Fig. 7 Partitioning of dry matter in 'Hass' avocado trees grown for 6 months in atmospheres of either 350 or 600 µmol CO_2 mol^{-1}. Columns represent means *(n=6)* ±*SE.* (Schaffer and Whiley, 2002). ***(Figure not provided)***

HOW CAN THE INDUSTRY ADAPT?

There appear to be many potentially significant impacts of climate changes on the avocado industry, some of which may be positive, some negative. There is a need to identify management strategies to either offset negative impacts or to take advantage of positive responses. Previous assessments of such adaptations have been made for other industries (e.g. Howden et al. 2003). One of the general conclusions from these analyses is that the best defence against future climate change is to continue to develop the capacity and knowledge to manage current climate variability more effectively.

Most of the anticipated climate changes point towards the need for a very high standard of orchard management in order to respond to the challenges that expected changes pose. Some of the expected changes may even see a need to consider a shift in orchard location (e.g. Schulze and Kunz, 1995). There is also a need to adapt marketing plans to accommodate anticipated changes in harvest times. Therefore the following potential management implications for growers and the industry may need to be considered.

Table 7. Potential implications for avocado orchard management as a result of anticipated climate change.

Issue	Potential management implications
Lower diurnal temperature range	Introduction of pollinator varieties in blocks currently planted to single varieties. More extensive use of growth regulators to achieve better fruitset.

Warmer night temperatures	Areas previously considered too cool may now have potential as avocado production sites. Areas such as the Toowoomba Range previously experiencing frequent fruitset failures may become more viable.
Higher summer temperatures	Increased irrigation requirements, increased water storage capacity, more accurate moisture monitoring systems and more efficient irrigation systems. Re-locate to cooler micro-climates or more southerly locations. Use of overhead evaporative cooling irrigation systems (Blight *et al.*, 2000). Greater need to reduce incidence of stress on ‘Hass’ by more careful management, use of mulch and use of growth regulants such as uniconazole (Sunny®) to improve fruit size (Wolstenholme, 2001).
Significantly warmer autumn and winter temperatures	In the long term it may be necessary to cease orchard operations in areas where it becomes too warm in autumn and winter to produce a good flowering. ‘Shepard’ may be successfully grown in more southerly districts.
Earlier maturity times and reduced on-tree fruit ‘storage’	Plan for earlier harvest times and address associated marketing issues. Assess market access and timing.
Phytophthora cinnamomi activity	Even greater attention required for the control of this disease:-Better drainage, eg. higher row mounding. Closer monitoring and attention to root phosphonate levels. Greater use of mulch. More effort directed to attaining recommended soil pH of 5.5 and high soil calcium levels. More precise soil moisture and nutrient management. Use of more tolerant rootstocks. Stricter orchard phytosanitary procedures.
Insect activity	Closer monitoring and more responsive management of insect pests and predators. Better control mechanisms
Increasing number of heat stress days	Greater need for effective management of *P. cinnamomi* to improve leaf cover. Efficient and effective irrigation scheduling and application system. Use of overhead evaporative cooling irrigation systems. Application of sunburn protection for fruit eg. Surround®, bentonite. Selectively harvest exposed fruit prior to expected high temperature periods. Select sites with greater water holding capacity in the root zone, eg. deeper loams. Greater use of mulch.
Increase in number of cyclones and storm events	Consider re-location of orchards to areas less prone to cyclones and other extreme weather events such as hail. Re-visit the use of windbreaks to reduce damage to trees and fruit. Canopy management systems implemented, not only to improve productivity and fruit quality but also to keep tree size smaller to reduce structural damage in storms.
Increase in frequency of droughts	Selection of orchard sites less prone to drought. Installation of adequate water harvesting and storage structures to capitalise on high rainfall events when they do occur. Greater need for the selection, installation and maintenance of effective moisture monitoring and irrigation scheduling systems. Installation and maintenance of more efficient and effective irrigation systems capable of adequately watering the whole orchard using less water and with a quicker turn-around. Effective use of under-tree mulching

	to reduce temperature in root zone, help maintain soil organic matter levels in the face of increased soil temperatures and reduce unnecessary evaporation. Allow for possible increases in irrigation demand and also consider risks to supply reliability.
Frost and cold weather during flowering	If frost risk declines, plantings could occur in locations currently unsuitable.

In order for adaptation to climate change to be successful there will be a need to incorporate both pre-emptive and reactive adaptive strategies. These will need to occur in conjunction with already changing social, economic and institutional pressures. With this in mind, adaptation measures aimed at reducing the negative impacts of climate change will have to reflect and enhance current 'best-practices' designed to cope with adverse conditions such as drought. Whilst a range of technological and managerial options may exist as indicated in Table 7, the adoption of these new practices will require:

1) confidence that climate changes several years or decades into the future can be effectively predicted against a naturally high year-to-year variability in temperature and rainfall that characterises these systems;
2) the motivation to change to avoid risks or use opportunities,
3) development of new technologies, and demonstration of their benefits;
4) protection against establishment failure of new practices during less favourable climate periods; and
5) alteration of transport and market infrastructure to support altered production (McKeon *et al*., 1993).

Adaptation strategies that incorporate the above considerations are more likely to be of value, as they will be more readily incorporated into existing on-farm management strategies.

WHAT ARE THE KEY RESEARCH CHALLENGES FOR THE NEXT FIVE YEARS?

We are in the early stages of assessing the impacts and consequences of climate change in horticulture in Australia. Growers are already managing avocado production within a very variable climate. The best defense in managing the impacts of climate change in any system is to improve on the management of current climate variability. The following are challenges for growers, industry and scientists to address as climates continue to change

- Understand current climate variability and how it might be managed more effectively, including the use of information packages or prediction systems such as Australian Rainman, and the use of seasonal climate forecasting
- Continue to monitor climate changes in existing production areas
- Identify those agronomic and physiological factors affecting avocado performance, which can be influenced easily by growers, to account for climate change as it is happening
- Determine the sensitivities of these factors in a changing climate

- Identify and discuss management options which growers and industry can use to manage climate variability and to be able to adapt to a changing climate
- Identify current “at risk” production sites and new areas that may be suitable for production, following climate change
- If expansion of the avocado industry is to occur, it will be important to ensure that climate factors have an appropriate weighting in the decision. e.g. develop an avocado site selection system similar to that produced by Queensland Department of Natural Resources and Mines for the Australian olive industry. This can take into account climate change factors
- Improving the reliability of climate change modelling outputs, to reduce the variation within future scenarios
- Keep abreast of developments in moisture monitoring systems and more efficient irrigation systems, including overhead evaporative cooling irrigation
- Continue research into development of rootstocks that are more productive, more tolerant of root rot and more capable of performing under the likely changes in climate
- Assess West Indian race avocados in rootstock and scion breeding programs as these are more suited to warmer conditions
- Continue to assess ‘Hass’-like alternative varieties that do not suffer the small fruit size problem found in ‘Hass’
- Continue to investigate less costly ways of controlling *Phytophthora cinnamomi* root rot
- Review avocado irrigation research in Australia and undertake any necessary research to fill any gaps in knowledge regarding efficient water use
- Calculate expected shifts in crop maturity times for different growing areas for use in marketing plans
- Calculate changes in expected on-tree storage times for those regions where this is currently an important marketing strategy
- Better understand and take advantage of CO_2 fertilization, and its effects on yield

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