The Potential Impact of Climate Change on Wool Growing in 2029

A research brief conducted by CSIRO Sustainable Ecosystems for Future Woolscapes

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Executive Summary

The most recent report of the Intergovernmental Panel on Climate Change (Watson, 2001) concluded that there is now strong evidence for a human influence on global climate and that these trends will continue for the foreseeable future due to continued emissions of carbon dioxide (CO_2) and other greenhouse gases from fossil fuels and other sources. Climate projections for Australia indicate that by 2030, mean annual temperature will have risen between 0.4 and 2 °C, there will be a higher incidence of extreme hot and cold days and there will an increase in climate variability, with a higher occurrence of El Niños. Rainfall projections are more complex, with mean annual rainfall predictions ranging from between –20% and +5% in the southwest to between –10% and +10% in the central east. Decreases are predicted as being most pronounced in winter and spring, with some inland an eastern coastal areas possibly becoming wetter in summer.

In terms of the Australian wool industry, these climate changes are likely to have implications for:

- pasture and fodder crops, with likely increased growth under higher CO_2 concentrations (and in some areas, higher summer rainfall). This will be generally offset by lower nutrient content and, in some regions, by the impacts of rainfall deficits. The availability and quality of pasture and fodder crops will also be affected by any increased in the frequency of droughts. Pasture composition is also likely to be affected.
- water resources are likely to come under strain, with water supplies being reduced in areas where evaporation increases and rainfall decreases and becoming more variable under a regime of more frequent extremes (both drought and high intensity rainfall).
- wool production and quality, with reduced productivity in marginal areas and possibly some increased productivity in higher rainfall regions. There is a potential for increases in vegetable fault where pasture composition changes (particularly in regard to weed content) and dust contamination due to increases in land degradation. There may be a reduction in wool fibre diameter in response to declines in pasture availability and quality, although this could be accompanied by a rise in the incidence of tender wool. Staple strength could also be affected, with both increases and decreases depending on location.
- animal health, with increased thermal stress (particularly in the north) and subsequent increases in animal water demand and susceptibility to pests and diseases (the range of which is also likely to be extended southward), as well as decreased reproductive and growth rates;
- land degradation issues, with greater stress on the land principally brought about by rainfall deficits and increased variability, leading to a greater focus on issues of land stewardship;
- competition from other agricultural activities, particularly in regard to cropping and water/land resources (an issue most likely to affect the high rainfall wool growing regions);
- national and international markets, with possible further reductions in demand for apparel wool fibre in response to rising temperatures. International production and supply markets may also shift, with wool growing areas of both New Zealand (western) and China (temperate) likely to be advantaged by climate change, whilst other areas in these countries being disadvantaged (the eastern and semi-arid/arid, regions respectively).

1. Introduction

Human activities have significantly increased the atmospheric concentrations of greenhouse gases and aerosols (e.g. pollutant particles and dust) since the pre-industrial era. The atmospheric concentrations of key anthropogenic greenhouse gases[1] reached their highest recorded levels in the last year, primarily due to the combustion of fossil fuels, agriculture and land-use changes (Figure 1). These human-sourced greenhouse gases affect the radiation balance of the globe, resulting in warming of the land surface, the oceans and the lower atmosphere (Houghton *et al*., 2001). Globally, the 1990s was the warmest decade in the instrumental record (1861–2001), with the three warmest occurring 1998 to 2001 (Figure 2). The increase in surface temperature over the 20th century is likely to have been greater than that for any other century in the last thousand years, with much of it being attributable to human activities (Figure 3; Mann *et al*., 1998; Houghton *et al*., 2001).

The direct aerosol effects are in the reverse direction (i.e. they have a cooling effect), but much smaller and more localised due to their short atmospheric residence time. Aerosols may also affect clouds significantly but this is not well quantified (Houghton *et al*., 2001).

An increasing body of observations gives a collective picture that the net effect of the above changes is already having flow-on impacts. The International Programme for Climate Change Third Assessment Report (Watson, 2001) identified over 100 physical processes and over 450 species and communities that are showing coherent changes across diverse regions which are consistent with these climate changes (see Appendix 1 for a summary). Although many of these changes are likely to interact with other, on-going variations in human activities and natural climate variability, the probability that these observed changes could occur by chance alone is considered by the IPCC to be negligible.

Although climate change is only one factor that will potentially affect Australian agriculture in the future, it is likely to increase the vulnerability of the sector. This is particularly true in regard to potential effects of climate change on water demand and supply brought about by the combination of warming, increased potential evaporation and reductions in rainfall. There will be additional stresses associated with the projected increases in drought frequency and severity (Pittock, 2003).

As one of Australia's most important agricultural industries, the potential effect of climate change on wool growing is of some concern. The wool industry comprises 7-10% of the gross value of agricultural production in Australia, earning between three and four billion export dollars per annum (Ashton *et al.,* 2000; Shafron *et al.,* 2002). Indeed, Australia is the largest producer and exporter of wool in the world, exporting 479 million kg of greasy wool in 2000-01 (2.4% of Australia's total exports), and accounting for 48.5% of global wool apparel in 2002/2003 (Australian Wool Innovation Limited, 2004). In 2001/2002, 95% of Australia's sheep flock was run on 40,000 broadacre farms, 27% of which received the majority of their income from sheep and wool. Around 55% of Australia's total flock is contained in the wheat-sheep zone, 33% in the high rainfall zone and 12% in the pastoral zone (Figure 4). Specialist wool producing farms accounted for 32% of Australia's wool output, with the majority of production coming from NSW (36%), Western Australia (23%) and Victoria (20%) (Australian Wool Innovation Limited, 2004; Shafron *et al.,* 2002). The fine wool proportion of the Australia clip has increased from 8.8% in the early 1990s to 30% in 2003 (Australian Wool Innovation Limited, 2004). However, there has also been a decline in global wool consumption brought about by a number of factors, including competition from other fibres, changing consumer tastes and competition for consumer income from other areas, such as house-hold appliances (Ashton *et al*., 2000). Correspondingly, both wool prices and wool production have steadily fallen since 1987, with the number of Australian farms running sheep also declining. It should be noted, however, that the average size of farm flocks has increased, with a higher proportion of wool growers selling lambs for slaughter. Despite the reduction in production and in prices, wool remains an important component of Australian farm incomes (Shafron *et al.,* 2002).

This report presents a brief overview of the potential effects of climate change on wool growing in Australia in 2029. The report has been commissioned by Future Woolscapes (a joint research project between Australian Wool Innovation and Land & Water Australia) and focuses on climate change scenarios for 2029, the impacts of climate change on Australia in relation to the Australian wool industry, issues of land stewardship and sustainability, the potential effects of climate change on Australia's main wool growing competitors (New Zealand and China), and future scenarios for wool growing in Australia taking into account both climate change and other factors affecting the sector.

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[1] carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and tropospheric (lower atmospheric) ozone (O_3)

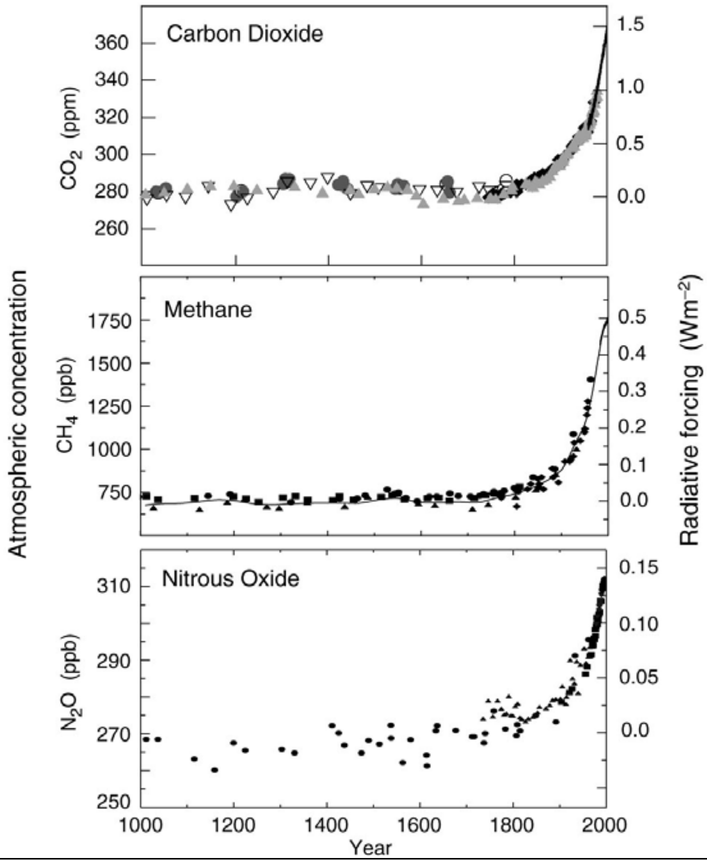

Figure 1. Global concentrations (ppm or ppb) and associated changes in radiative forcing (W/m^2) for carbon dioxide, methane and nitrous oxide from the year 1000 to the present (Houghton, 2001).

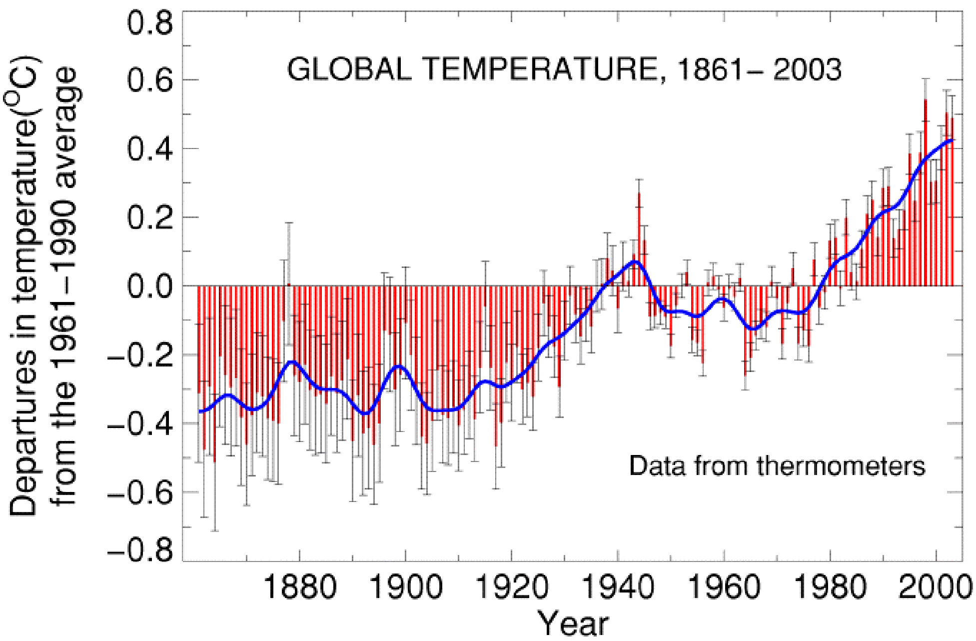

Figure 2. Global temperature anomalies (°C) from 1861 to the present from the Hadley Centre, UK Meteorological Office (www.meto.gov.uk).

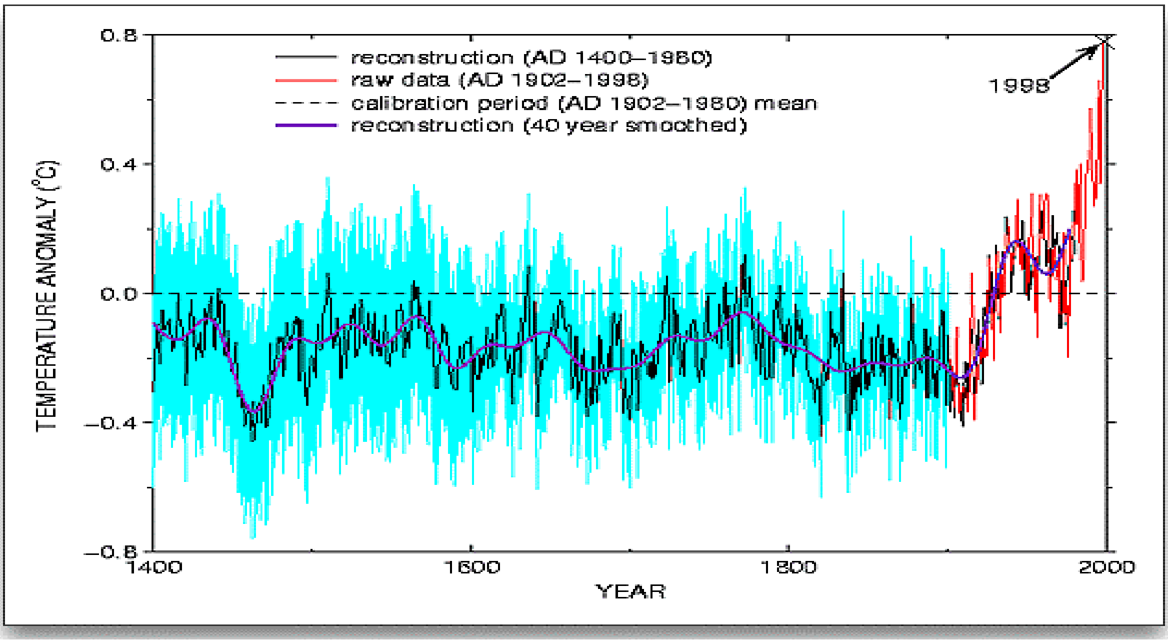

Figure 3. Temperature of the Northern Hemisphere from reconstructions from proxy data (AD 1400-1980) and instrumental record. (AD 1902-1998) (after Mann et al., 1998).

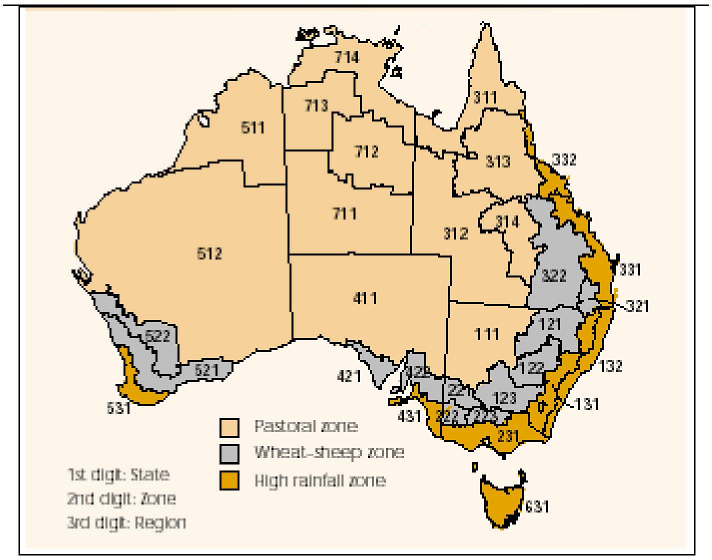

Figure 4: Sheep producing regions in Australia. (Shafron et al., 2002)

2. Climate change scenarios for 2029

2.1 Changes that have occurred in the regions occupied by the wool industry

There have been a range of climate-related changes in the regions occupied by the Australian sheep industries over the past decades to centuries. These include temperature shifts, changes in mean annual rainfall, increased rainfall intensity, changes in streamflows and in snow cover and depth.

Recent warming trends have been identified for Australia in high-quality surface temperature records (e.g. Torok and Nicholls, 1996) and are supported by data from dendrochronological (tree ring) studies (e.g. Cook, 1995). Annual minimum temperatures have increased by an average of 0.85 ^{o}C per century and maximum temperatures by 0.39 ^{o}C per century across Australia (Plummer *et al*., 1995; Torok and Nicholls, 1996). However, these increases have been neither spatially nor temporally uniform (Figure 5). The trend to warmer temperatures appears to have already reduced frost frequency and duration (Stone *et al.,* 1996), increasing, for example, Australian wheat yields (Nicholls, 1997). In the warmer regions of Australia, rising temperatures have increased the frequency of heat stress in livestock (Howden and Turnpenny, 1997). These increases in temperature will have also increased evaporation rates (Howden, 2003).

Australian rainfall has also increased slightly over the past century, with part of the trend influenced by the period of heavy rainfalls in the mid-1970s (Lavery *et al.* 1997, Suppiah and Hennessy, 1998). However, again this trend has been spatially variable with sharp declines in some regions (e.g. south-west WA) but steady increases in others (Figure 6). One region experiencing the latter is south-east Australia, where mean rainfall has increased by about 17% over the past 100 years (CSIRO Atmospheric Research, 2003). There have also been significant increases in heavy rainfall by between 20-30% across New South Wales in autumn and summer (Hennessy *et al*., 1997). High intensity rainfall events are those that lead to increased flood risk.

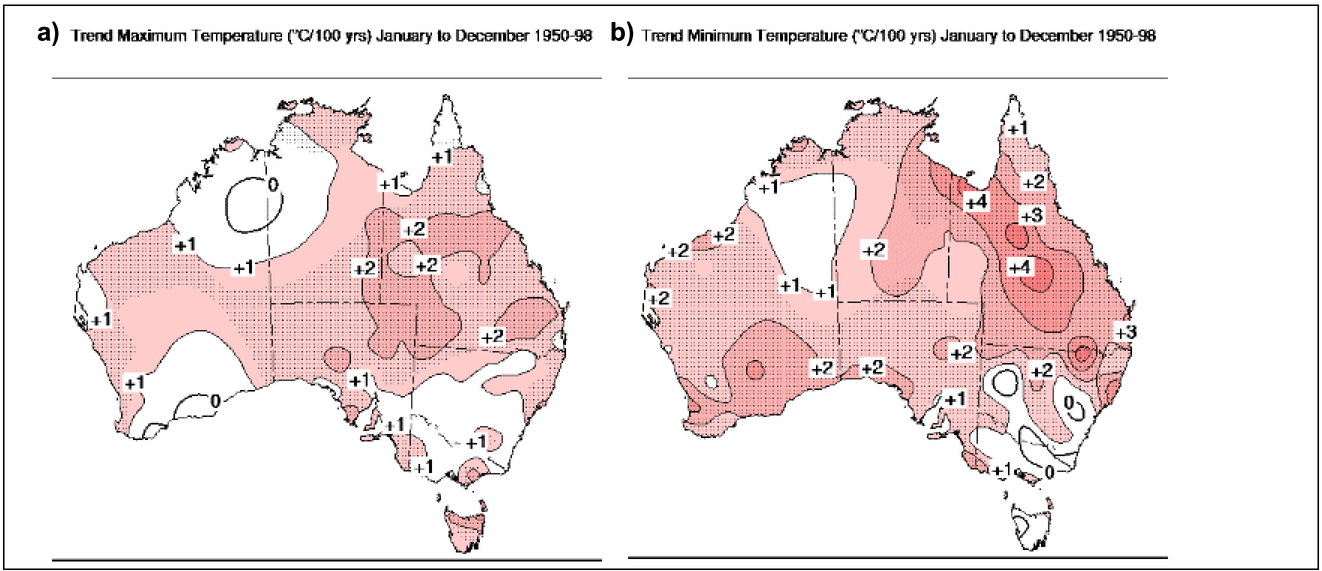

Figure 5. Trends in a) maximum and b) minimum temperatures across Australia between 1950 and 1998. Trends are measured in ^{o}C per hundred years. Bureau of Meteorology website.

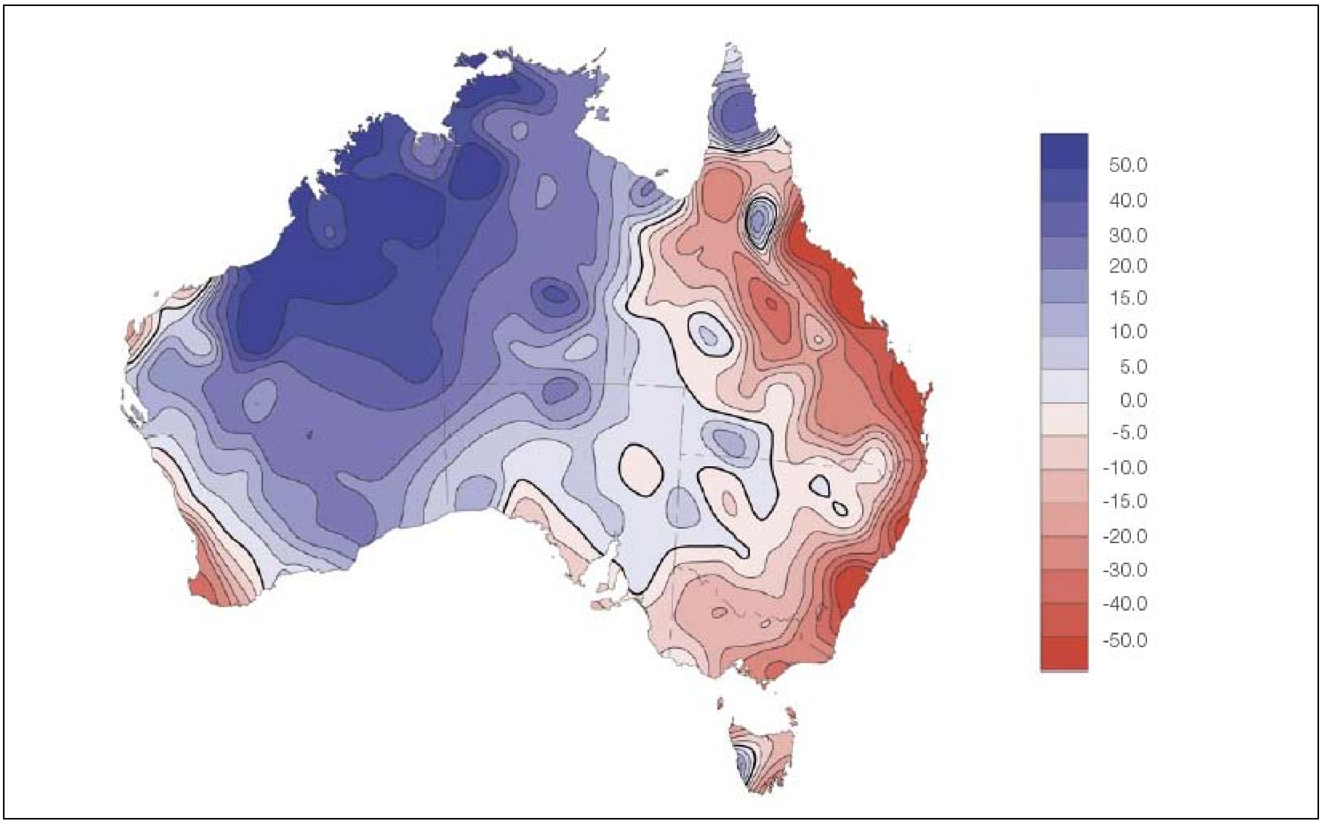

Figure 6: Trend in annual total rainfall 1950-2003 (mm/10 yrs). (Bureau of Meteorology, 2004).

2.2 Climate change scenarios

The IPCC Third Assessment Report (Houghton *et al.,* 2001) assesses that the accumulation of greenhouse gases in the atmosphere over the past 100 years or so already means that we are committed to some further, though relatively small, climate change. However, the key driver for concern is the very substantial climate changes that are thought likely to arise from future greenhouse gas emissions.

The IPCC Special Report on Emissions Scenarios (SRES: Nakicenovic and Swart, 2000) developed a set of possible scenarios for emissions of greenhouse gases and their consequences for atmospheric concentrations. The scenarios took into account a large range of possible population, socio-economic, technological and policy pathways, merging them into internally consistent 'storylines'. These are not intended to be predictions but just plausible development paths. Most of the scenarios resulted in increases in greenhouse emissions, although some decreased them (Figure 7a). However, in all cases atmospheric concentrations of greenhouse gases increased over the next 100 years (Figure 7b) leading to increases in global average temperature and other climatic changes. This increase in atmospheric CO_2 concentrations even in low emissions scenarios is due to the sources of emissions still being greater than the oceanic and land-based sinks. Stabilization of CO_2 concentrations at any level requires eventual reduction of global CO_2 net emissions to a small fraction of the current emission level whereas stabilization of emissions of shorter-lived greenhouse gases such as CH_4 leads, within decades, to stabilization of their atmospheric concentrations.

For the six illustrative SRES emissions scenarios in Figure 7, the projected concentration of CO_2 in the year 2100 ranges from 540 to 970 ppm, compared to about 280 ppm in the pre-industrial era and about 372 ppm currently. Levels for 2029 are projected to range between 400 and 480 ppm. The different socio-economic assumptions (demographic, social, economic, and technological) result in the different levels of future greenhouse gases and aerosols. Further uncertainties, especially regarding the persistence of the present removal processes (carbon sinks) and the magnitude of the climate feedback on the terrestrial biosphere, cause a variation of about -10 to +30% in the year 2100 concentration, around each scenario. Therefore, the total range is 490 to 1,260 ppm (75 to 350% above the year 1750 (pre-industrial) concentration). Concentrations of the primary non-CO_2 greenhouse gases by year 2100 are projected to vary considerably across the six illustrative SRES scenarios.

The significance of these possible changes in atmospheric CO_2 become evident when viewing on a longer term basis. Figure 8 shows atmospheric CO_2 changes over several ice age cycles using information from the Vostok ice core (which extends 420,000 year before the present) as well as more recent data. It is apparent from inspection of this record that the earth system self-regulated CO_2 concentrations between both upper and lower bounds. The current concentration (372ppm) is outside these bounds and future trends take us further outside. It may be important to note that this ice core record encompasses the whole history of our species, *Homo sapiens* (about 90,000 to 140,000 years depending on the authority). Hence this change in CO_2 concentrations and the accompanying climate changes we anticipate are outside the bounds of human experience and possibly outside the self-regulating bounds of the earth-system. Furthermore, no readily acceptable set of policies or technology seems likely to be able to deflect us from this trajectory.

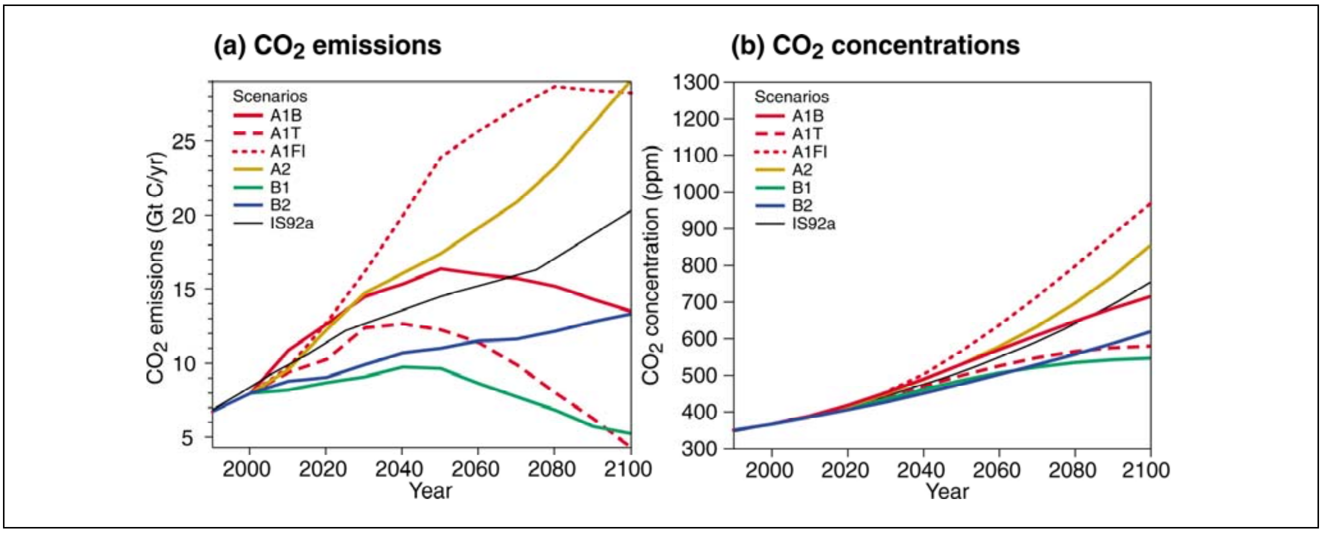

Figure 7. Scenarios of a) future CO_2 emissions and their consequences for b) future atmospheric CO_2 concentrations. (Nakicenovic and Swart, 2000).

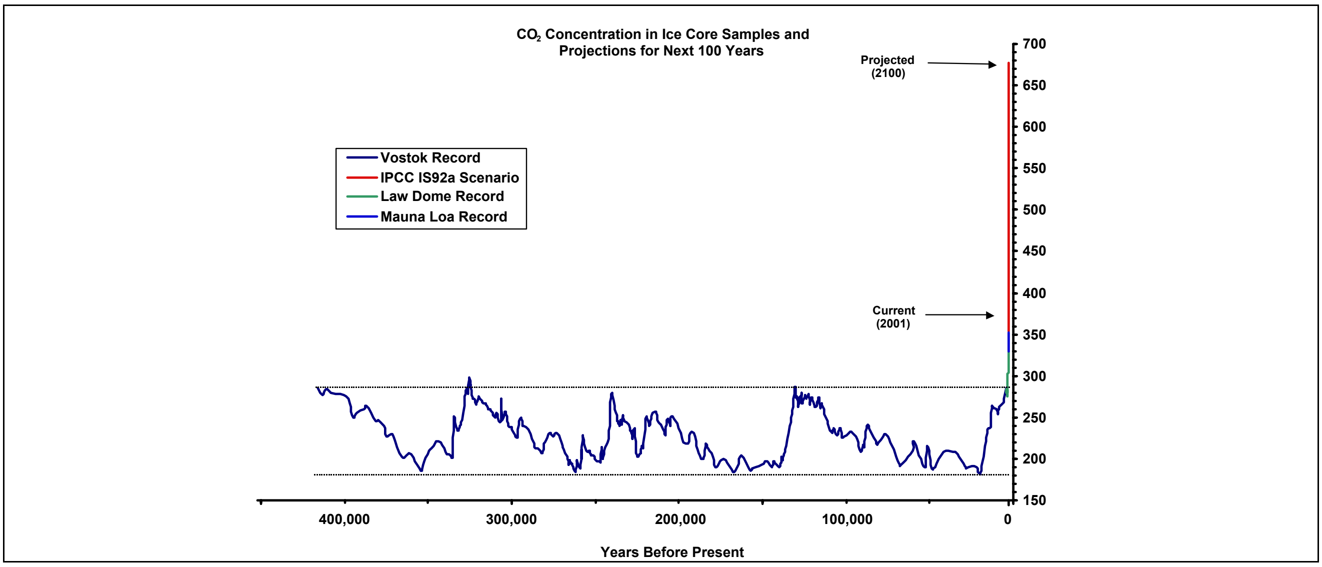

Figure 8. Atmospheric CO_2 levels measured over the past 420,000 years from the Vostok ice core, the Law Dome ice core and the Mauna Loa measurements combined with mid-range projections of concentrations for the next 100 years (CSIRO, 2001).

The implications for such changes for Australian temperatures and rainfall are displayed in Figures 9 and 10. The ranges in the projections are related to both modelling uncertainties and uncertainties over the level of future greenhouse gas emission (Figure 7). By 2030, the average annual temperature is projected to rise between 0.4 and 2 °C over most of Australia, with an accompanying increase in the likelihood of extreme hot or cold days. Projected changes in precipitation by 2030 are more complex and less certain. They range from –20% to +5% in the southwest to –10% to +10% in the central east (see Figure 10). Decreases are predicted as being most pronounced in winter and spring, with some inland and eastern coastal areas possibly becoming wetter in summer, and some inland regions becoming wetter in autumn. The models suggest that more extreme wet events would occur in areas where average rainfall increases, whilst more dry phases would occur where average rainfall decreases. The incidence of El Niños may be enhanced by global warming. However, most of the models simulate more frequent heavy rainfall events and flooding in both areas where average rainfall increases and slightly decreases, with reductions in extreme daily rainfall where average rainfall declines significantly. Evaporation is likely to increase under warmer conditions, which, when combined with potential declines in rainfall, may further decrease available moisture (CSIRO, 2001).

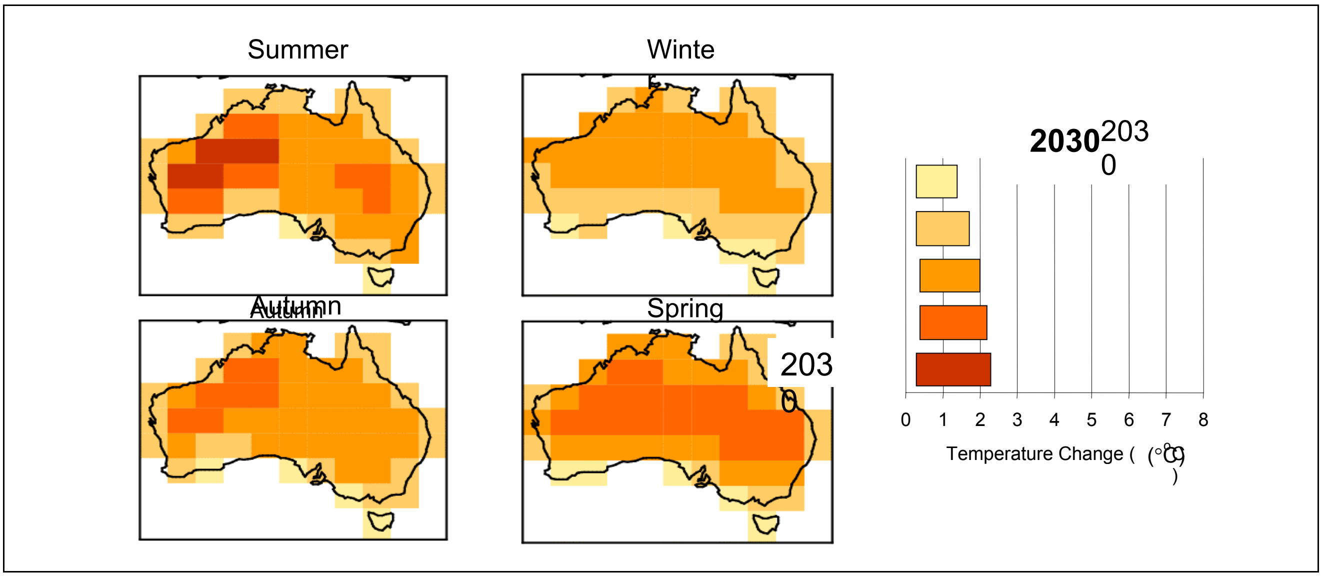

Figure 9. Average seasonal and annual warming ranges (°C) for around 2030 relative to 1990. The coloured bars show ranges of change for areas with corresponding colours on the maps (CSIRO, 2001).

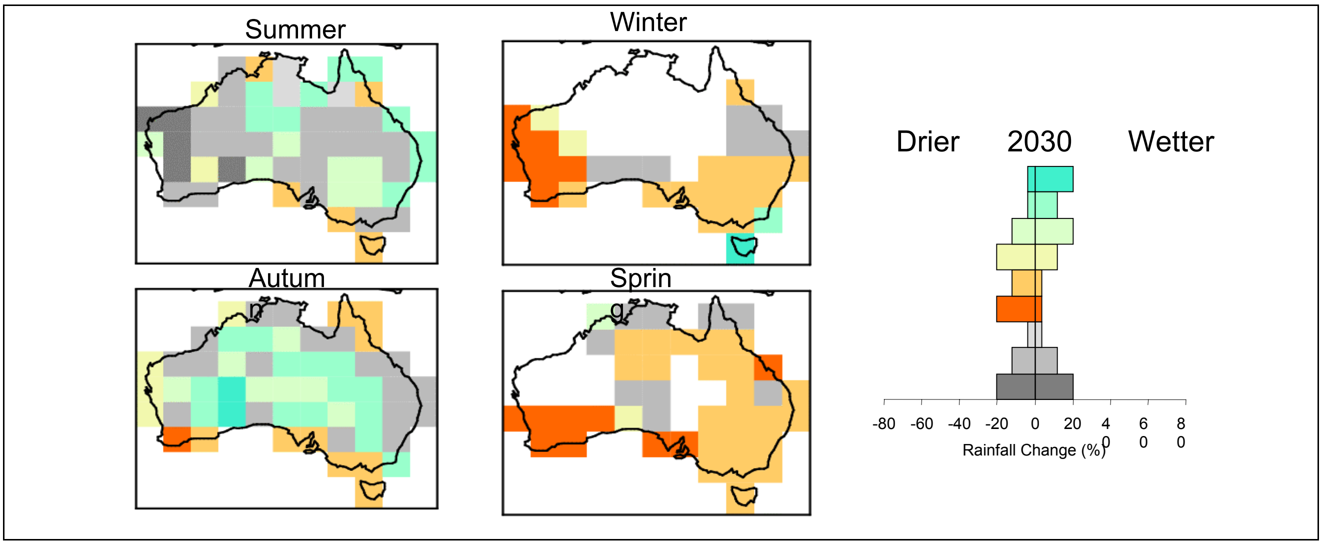

Figure 10. Average seasonal and annual rainfall change (%) for around 2030 relative to 1990. The coloured bars show ranges of change for areas with corresponding colours on the maps. (www.dar.csiro/publications/projections2001.pdf)

3. Impacts of climate change on Australia

Climate change is likely to affect a range of variables associated with wool production. These include impacts on pasture and fodder crops, the quality and quantity of wool production, animal health and reproduction and water availability and demand. Given that 55% of Australia's sheep flock is in the wheat-sheep zone, the effects of climate change on wheat production (Howden and Jones, 2001) are also likely to have an impact on wool enterprises. However, the effects of climate change on associated cropping enterprises are outside the scope of this paper and the following sections focus on the direct impacts of climate change on the wool industry.

3.1 Impact on pasture/fodder crops

The impact of climate change on pastures and fodder crops will vary between geographic and agro-ecological systems because of the expected differences in impact of climate change between regions. However, the uncertainty concerning the direction and magnitude of changes in climate means the exact effect on pastures is unclear. It is likely that in 2029 the impacts of climate change will be noticeable, although not dramatic and will be largely manifested through changes in pasture growth (both increases and decreases) and quality (more often declines), and greater inter-annual variability in pasture production. Various studies suggest that the changes that eventuate in pasture growth, composition and production will be dependent on the actual combination of CO_2, temperature and rainfall conditions that occur.

3.1.1 Effects of elevated CO_2

The higher atmospheric CO_2 concentrations that are inevitable in the future (optimistic scenarios suggest stabilisation at about 500 ppm; pessimistic ones see 900 ppm being reached by 2100 (Nakicenovic and Swart, 2000) will, with high certainty, increase the above-ground plant productivity in rangelands. Experimental evidence from a large number of studies shows that increases of atmospheric CO_2 concentrations to 700 ppm could significantly increase productivity of plants, ranging from 10-15% in mesic environments to 20 to 40% in water-limited situations (Wand *et al.,* 1999), with doubling of above-ground production in dry years (Stokes *et al,* 2003). Expression of these CO_2 responses is dependent on other variables such as temperature, rainfall, soil moisture and soil nutrient availability, especially nitrogen (Fischer *et al.,* 1997*;* Suter *et al.,* 2002) leading to variable responses in experiments. This is especially so after several years when pasture species composition has changed under elevated CO_2 concentration owing to differential increases among species of the number of seeds produced (Edwards *et al*., 2001) and other competitive effects (Smith *et al.,* 2000). However, any increases in production may be offset by projected reductions in rainfall and increases in evaporation. For those grazing lands where a small net drying is projected (i.e. about 10%), the effects may approximately cancel each other out, resulting in unchanged primary production. In the case of greater rainfall reductions and/or large increases in temperature, there will be reductions in plant production.

The main mechanism raising plant production with higher CO_2 concentrations is an increase in the efficiency with which plants convert water into dry mass. Since most grazing lands in Australia are water limited at some time of the year, the effect will be widespread, although differing in terms of degree with geographic location. The CO_2 effect applies to both C_3 plants (such as trees, forbs and temperate grasses) and C_4 plants (such as tropical grasses), with the stimulatory effect levelling off as the concentration rises. Some evidence suggests that in near-natural grasslands, most of the effect is expressed below 500 ppm. There are marked differences in response to CO_2 between species. There has been speculation that in semi-arid areas there may be increased competition between trees and grasses with higher CO_2 levels. If woody plant growth were favoured over grass growth, a possible consequence would be accelerated invasion of trees and shrubs into grasslands, suppressing grass production. Note that changes in temperature, rainfall, fire frequency and fire intensity could also be implicated in shifts in the tree-grass balance, alone or acting in concert with CO_2 increase (Archer *et al*., 1995) with consequent effects on herbage availability. If burning management is adjusted, however, to higher grass biomass with increased CO_2 concentrations, there may be increased opportunities to control woody plant establishment (Howden *et al*., 2001a).

3.1.2 Regional trends

There are likely to be north-south differences in the response of pasture production to climate change, as well as differences between more arid inland areas and more mesic regions. Crimp *et al.* (1999) suggested that a lengthening of the growing season would result in a potential increase in pasture growth in Queensland's grazing lands if nutrients are not limiting, especially where pastures are dominated by C_4 grasses.

In many southern farming regions little change in pasture production is anticipated, although in some areas a shortening of the winter growing season may reduce the amount of forage available. This may have implications for lamb survival and growth. However, in experiments by Lilley *et al.* (2001) elevated $C0_2$ and warming improved herbage yield of mixed sub-clover and phalaris pastures by 23%. Much of the observed increase was due to a positive growth response by the clover rather than the grass (a C_3 species). Indeed the legume component of the sward increased relative to the grass, suggesting it may be easier to maintain sub-clover in pastures. In addition, there may be greater opportunity for summer-growing forage species in some areas.

Many inland areas are expected to see marked reductions in rainfall and increased inter-annual variability associated with the El Nino-Southern Oscillation. A consequence will be lower and more variable pasture production (Crimp *et al.* 2003), since the reduction in rainfall will exceed the level at which increased $C0_2$ can buffer declines in growth.

Changes in the nutrient value of pastures may also occur both in natural pastures in the rangelands and in sown pastures in more mesic areas. Experiments have generally shown that elevated concentrations of CO_2 significantly decrease leaf N-content, increase non-structural carbohydrate, but cause little change in digestibility in those species studied so far (Lilley *et al.* 2001). It appears that the total content of protein is relatively unchanged, but it is diluted by relatively easily-digested carbon-based substances such as sugars and starches. The implications of these changes differ between production systems. In those with high nitrogen forage (e.g. temperate pastures) the fodder generally has more protein content than can be usefully used by stock owing to insufficient metabolisable energy in the herbage for its full utilisation. In such situations, the effects of CO_2 are likely to increase energy availability, increasing nitrogen processing in the rumen, increasing productivity. In contrast, in situations which are chronically nitrogen deficient (many rangelands for part of the year), the effect of CO_2-induced nitrogen dilution may be to exacerbate the existing problems. This effect may be compounded if there is concurrent warming as warmer conditions tend to significantly decrease non-structural carbohydrate concentrations and digestibility, particularly in tropical species, while also slightly reducing leaf N-content (Wilson 1982).

Early expectations were that shifts in the distribution of native C_3 and C_4 grasses were possible in the rangelands under global change, with C_4 grasses becoming more abundant in the south. However a study by Howden *et al.* (1999a) indicated the southward migration of the zone where C_4 grasses dominate under combined climate change and CO_2 increase was likely to be limited. If such a change does eventuate, an increase in the proportion of C_4 grasses at the expense of C_3 species would represent a decline in the quality of pastures for livestock production because the former grasses tend to contain less protein, more lignin and less easily digested nutrient than C_3 grasses. Dietary supplementation may be required to counteract this and maintain production levels. C_4 grasses will also produce peak growth in the warmer months, assuming adequate moisture for growth is available.

C_4 shrub species such as *Atriplex vesicaria* (bladder saltbush), which is an important species in much of the southern sheep rangelands, might benefit from a shift to more summer rainfall in terms of plant growth. However, the capacity of this species to reproduce may be adversely affected because of the requirement for low temperatures (below 20°C) for germination. A consequence could be the contraction of the distribution of the shrub.

In the sheep rangelands the incidence of native woody weeds may increase (both in distribution and abundance) as areas become increasingly dominated by summer rainfall patterns. This would reduce the amount of forage produced and create other problems, such as increasing mustering difficulty and costs. Other weeds may also spread. For example, modelling of populations of prickly acacia, *Acacia nilotica*, an introduced shrub currently present in the Mitchell grasslands in Queensland, suggests increased risk of expansion of its range both southwards and into more arid inland areas under anticipated climate change (Kriticos *et al.,* 2003). Prickly acacia reduces pasture production, impedes stock access to water points and increases mustering costs and soil erosion.

Greater opportunities for the growing of summer fodder crops may emerge in some areas, providing more abundant feed at this time of the year, particularly for areas with a usually winter-dominant pasture. However, it may be that crop production is favoured over fodder production in these areas.

3.2 Impact on wool production –quality and quantity

There are several potential impacts of climate change on the quantity and quality of wool produced. Most effects will arise indirectly through changes in pasture conditions rather than being direct effects of climate. However, one early study indicated that an increase in subdermal temperature of 5°C resulted in increased wool growth, but if the temperature was further increased, wool growth declined and then ceased (Jolly and Lyne, 1970).

There is little data specifically on the implications of climate and pasture change for wool and sheep production. Most investigations (modelling studies) have involved the beef industry in the rangelands of Queensland. However, this work does provide some insights about possible outcomes for the sheep and wool industries.

Hall *et al.* (1998) found that safe carrying capacities would be increased between 7 and 27% for beef properties in parts of Queensland, such as the south-east. In central Queensland, an area where sheep are also run, they determined that decreases in rainfall of 10% would result in decreases in carrying capacity of an equivalent amount. Conversely, they identified that an increase in rainfall would produce an equivalent increase in carrying capacity. Both increases in temperature and a doubling of CO_2 alone were found to increase carrying capacity by as much as 30% and 14% respectively. An important finding was the potential for increased CO_2 to buffer declines in pasture production due to increases in temperature or declines in rainfall. Hall *et al.* (1998) also reported potential increases in live weight gain of cattle.

The effects on wool production per head and per hectare will therefore be dependent on the changes that occur in climate and pasture variables for particular regions. Production will decline in more marginal areas with decreases in pasture growth and quality. Fibre diameter is also likely to be influenced by changes in pasture yields and quality, with decreases in response to declines in pasture availability and quality. While this may actually be a desirable outcome to some extent, with greater variation in forage availability between seasons it might be accompanied by a rise in the incidence of tender wool. In general, staple strength could be affected, both with increases and decreases, again depending on the location and what that means for the nature of climate changes actually experienced. Furthermore, ewes experiencing low feed intake during gestation produce lambs in which secondary follicle production has been impaired, with consequences for long-term wool production (Entwistle, 1974).

Clean wool yield may decline with increases in vegetable fault in areas with augmented pasture yields or if there is a change in pasture composition (eg. increases in grass or legume components leading to more grass seeds or medic burrs). In those regions where climate change will result in reduced rainfall or greater inter-annual variation in rainfall, and consequently an enhanced risk of land degradation and erosion (Crimp *et al.* 2003), it is likely that dust contamination of the fleece will increase.

Whether changes in climatic conditions would dictate a change in the preferred breed or strain of sheep is not clear. If this was to occur, it would possibly involve the displacement of Saxon merinos in the higher rainfall areas with Peppin or even SA strong wool merinos that are more suited to harsher climates. This would represent a shift to the production of coarser wools, although a higher cut per head might increase the size of the wool clip.

3.3 Impact on animal health and reproduction

Climate change is expected to affect sheep production through direct impacts of thermal stress on reproduction, and indirect effects on animal health and growth. These aspects are discussed in subsequent sections.

3.3.1 Thermal stress

Many livestock in Australia are already subjected to periods in the year when there are high levels of heat stress. The frequency of such days declines markedly from north to south across the continent (Howden *et al.*, 1999b). Increased thermal stress on animals is expected as temperature and humidity levels increase over much of the continent (Howden *et al.* 1999b). This will occur not just in tropical and sub-tropical areas, although the implications will be more severe in these zones. Higher thermal stress will be manifested through an increased frequency of days where the daily temperature-humidity index (THI) exceeds a critical value (i.e. the frequency of days with THI > 80 is expected to increase 138% according to mid-range climate change scenarios). Already a significant increase (~60%) in the incidence of stress days has occurred over the last 40 years in many parts of Australia. Further increases in thermal stress will reduce animal productivity through lower growth due to appetite suppression (Alexander and Williams 1973), decrease reproductive rates and increase concerns about animal welfare in intensive livestock handling activities, such as live sheep exports (Howden *et al.*, 1999b). In contrast, rising temperatures, in particular minimum temperatures, may result in a reduction in the frequency and severity of cold-stress events, such as conditions which foster high lamb mortality. There has been little research on this topic.

Another possible consequence of increased thermal stress is higher water demand by livestock, which would increase the tendency of sheep to loiter near water points and further reduce feed intake. Increased loitering near water, together with the tendency for many pastoralists to be too slow to reduce stocking rates under worsening seasonal conditions, will contribute to more occasions of land degradation in the rangelands. Some areas in south-west Western Australia and south eastern Australia show no tendency in climate forecasts towards higher heat stress, although there is a general migration of heat stress zones from north to south across the continent. This will also increase animal welfare concerns related to intensive livestock handling activities such as live sheep exports (Howden *et al.* 1999b), and on-property activities like mustering. These results suggest that further selection for livestock lines with effective thermoregulatory control will be needed in the future, however the correlation of high heat stress tolerance and lower productivity characteristics means that the search for effective adaptation options will be challenging.

The combination of lower reproductive rates, poorer growth and survival of lambs and reduced growth of adult sheep, have the potential for making some areas where sheep are currently grown less suitable for sheep production. Presently, sheep production is limited in northern Queensland and north-western Western Australia, partly because poor reproduction rates make it difficult to produce enough lambs to maintain a viable flock (Alexander and Williams, 1973). This situation may worsen under expected climate change.

Overall, these results suggest that further selection for livestock lines with effective thermoregulatory control will be needed in the future. However, the correlation of high heat stress tolerance and lower productivity characteristics means that the search for effective adaptation options will be challenging.

3.3.2 Pests and diseases

The potential exists for the health of sheep to be adversely affected by climate change due to the anticipated increased incidence of pests and diseases. Much of this will be related to changes in the abundance and distribution of insects, many of which are vectors for disease. For example, under a climate warming scenario of increased summer rainfall, projections indicate a southward expansion of the future distribution of the insect vector of blue-tongue disease in Australia, *Culicoides wadia*. Its current limit is the north coast of NSW, but in future it may extend over the entire NSW coast, and permanently establish in SA and WA (Sutherst, 1990). The distribution of many tropical parasites is also expected to expand polewards (Sutherst, 2001).

With more humid conditions and greater summer rainfall, the incidence and frequency of blowfly strike on sheep is also expected to rise in response to increased numbers of blowflies and greater susceptibility of sheep (Sutherst, 1990). Treatment costs and/or sheep mortality are likely to be higher, and production and wool quality may decline. Other insects could increase in abundance (eg. the bush tick, *Haemaphysalis longicornis*, which would spread southwards), as could internal parasites as they benefit from greater survival on pastures due to shorter, milder winters. However, pest and parasite abundance might also be more variable in response to more variable seasons. Parasites may appear earlier in the season and go through more generations each year. On the positive side, lice and keds are expected to decline with global warming (Sutherst, 1990). How afflictions such as mycotic dermatitis would respond is unclear. Unfortunately there have apparently been no detailed studies of such issues to date.

There is the potential for a reduction in the nutrition of sheep in response to higher proportions of poorer quality forage species and/or lower nutritional content of existing species. This, in turn, could lead to the reduced immunity to disease in sheep (Coop and Holmes, 1996). However, Sutherst (2001) suggested that this effect might be offset by higher forage availability and a longer growing season.

3.3.3 Reproduction

Studies of the reproductive physiology of sheep in the arid zone indicate that heat stress is a major factor in lowering reproductive performance. Heat stress can degrade ram fertility (which is linked to increased failure of fertilisation due to defective gametes) and increase neo-natal mortality in lambs (Entwistle, 1974). This suggests that increased heat stress associated with climate change will adversely affect the reproductive performance of sheep in areas where temperature and humidity increases occur. Heat stress is not considered to directly affect oestrous activity in sheep, although an indirect effect may arise through nutritional stress due to limiting time spent grazing, and through poorer quality pastures. There is the potential for such indirect effects on oestrous to be negated through the use of supplements.

Sheep that are poorly adapted to heat stress suffer increased levels of embryonic mortality when exposed to continuously hot conditions, but ewes acclimatised to high temperatures and subjected to diurnally fluctuating temperatures show no such effects (Ryle, 1961). Heat stress has also been shown to result in reduced foetal growth. Mortality in the resulting lambs is higher than in lambs produced during cooler conditions (Alexander and Williams, 1973).

Plain-bodied sheep are more tolerant of heat than wrinkly ones, and are consequently more robust in terms of reproduction. Stronger selection for this trait may, therefore, be an important strategy to minimise detrimental effects on reproduction, particularly where producers currently favour sheep with some wrinkles.

3.4 Impact on water availability and demand

Climate change is likely to affect our water resources by increasing demand, changing surface water and streamflow regimes (e.g. flooding), and through possible affects on groundwater, such as depth to surface and water quality.

Water demand by livestock is strongly related to temperature, and is therefore likely to increase as temperatures rise in the future. For example, Howden and Turnpenny (1997) determined that stock water requirements are likely to increase by around 13% with a temperature increase of 2.7^{o}C, with further and non-linear increases if for further temperature rises. Higher water use rates by livestock mean that they will be unable to travel as far away from watering points, limiting use of the grazing resource in extensive grazing operations and tending to increase grazing pressure near watering points.

Reductions in rainfall across much of southern Australia and increases in evaporation rates with higher temperatures may combine to make surface water more scarce in many grazing lands as well as accelerate the depletion of small water storages (e.g. farm dams). Streamflows are projected to decrease significantly in many parts of Australia. For example, Arnell (1999) found marked decreases in runoff of 12 to 35% over the Murray-Darling for the year 2050. However, Arnell notes that the potential increases in rainfall intensity increase streamflow variability and can increase the chance of flood conditions. Higher temperatures and lower flows may also increase blue-green algae blooms (Viney *et al*., 2003) and also potentially increase salt concentrations.

The implications of climate change for groundwater are uncertain and are likely to vary markedly from place to place, depending on the rapidity of subsurface flows, the nature of the re-charge zone and the nature of the climate changes (e.g. higher rainfall intensity may increase recharge in some places). Generally, elevated CO_2 levels will increase groundwater recharge by between 5 and 20% if there are no alterations in climate (e.g. Howden *et al*., 1999a, van Ittersum *et al*., 2002). However, if there are significant reductions in rainfall from climate change, this effect will be over-ridden and reductions in recharge may occur.

3.5 Impact on land degradation issues

During periods of reduced rainfall and plant-cover, grazing lands become highly susceptible to soil erosion. This process serves to reduce pasture productivity through loss of valuable soil nutrients (McKeon and Hall 2000). In areas where climate models simulate increases in extreme daily rainfall, in conjunction with reductions in annual rainfall amounts (this applies to some extent across most of southern Australia), soil erosion may become an increasingly important management consideration.

Several studies (e.g. Howden *et al*., 1999a; van Ittersum *et al.,* 2003) suggest that recharge below the root zone is likely to increase with higher levels of atmospheric CO_2. This recharge is the driver for dryland salinity, consequently CO_2 elevation could increase the risk and potential area affected. However, as noted above (section 3.4) reductions in rainfall of about 10% would generally offset the influence of CO_2. Rainfall reductions greater than this will tend to result in a reduction in recharge. In some situations, recharge could effectively cease.

The loss of plant community integrity with climate changes partly underlies the predictions of accelerating invasion by 'alien' plants (i.e. weedy species are the ones most likely to proliferate). The consequences for animal production from grazing lands are generally negative, since highly palatable species are typically not among the successful invaders. The consequences for the conservation of grazing land biodiversity could be serious.

4. Climate change, land stewardship and sustainability

By 2029 there will be some (minimal) change in climate and direct impact on wool production. More significant, however, will be the recognition that climate change is real, continuing, very serious, and caused by human actions. With this realisation there is likely to be growing demand and acceptance that society has a responsibility to minimise the impact on the environment of climate change and limit the extent of future climate change. These efforts are likely to have at least as bigger impact on wool production as climate change itself.

4.1 Pressure for increased focus on land sustainability issues

Large amounts of public funding have been committed to issues of sustainability of rural land through programs such as the Natural Heritage Trust (NHT) and the National Action Plan for Salinity and Water Quality (NAP). Much of this has been directed towards monitoring and evaluation projects. It is anticipated that there will be a public expectation for these investments to be effective. In addition, there has been a notable increase in the awareness of and focus on issues of land stewardship (Curtis, 1997; Crosthwaite, 2001; Pahl, 2003). This is highly compatible with the growing desire of graziers to increase the long term productivity of their farms (Cary and Wilkinson, 1997), and also with the potential introduction of quality assurance programs that provide market access (McGauchie, 1998; Natural Resource Management Ministerial Council, 2002; Pahl, 2003).

One area of concern for stewardship of rural lands is biodiversity. The options for biodiversity management in grazing lands under climate change are currently mostly speculative. The optimal distribution of protected areas may have to be re-thought, with greater emphasis on their resilience in the face of climate change and exotic invasions, and greater emphasis on maintaining the existing conservation estate, particularly in 'refuge' areas. Existing conservation management activities may need reinforcement and increasing attention will be needed to manage for conservation on the 'matrix lands' between protected areas (van Jaarsveld *et al*., 2003). Even if a landscape can be designed to be 'permeable' to migrating species, the rate of climate change is likely to exceed the dispersal rate of all but the most mobile organisms (e.g. leading to the likelihood of more weeds). Some form of assisted dispersal may be raised but this opens up various issues of ethics, management and cost-effectiveness. *Ex situ* conservation (i.e. in zoos etc) is a strategy of last resort, but may be a necessary insurance policy for a few iconic species.

Concerns about land sustainability and stewardship issues have been generated by the acknowledgement that good land management is critical (Natural Resource Management Ministerial Council, 2002) and that there is a growing market for 'clean and green' production (Crosthwaite, 2001). As it becomes increasingly evident that humans are clearly impacting on global climates and that this in turn is having far reaching consequences for global production, health and lifestyle, it is hard not to see that there will be increasing expectations to cut down our impact at regional to local scales. From this, it follows that the land stewardship ethic will become more important, not less, into the future.

4.2 Greenhouse gas emissions and sinks

The implications of this issue are unclear for the wool industry. Australia has signed but not ratified the Kyoto Protocol. At the moment, there are not enough nations with enough emissions that have ratified the Protocol for it to come into force. If the Protocol does come into force without Australian ratification, we cannot participate in any emerging global carbon trading market. The Protocol specifically allows nations to include grazing land management as an 'Additional Activity' for carbon sink management. Whilst the grazing lands used by the wool industry could feasibly be a large sink for carbon in total, they are likely to be a small sink on a per hectare basis. This is likely to raise the relative cost of monitoring and verification against any financial benefit from establishing a carbon sink – even before allowing for any input costs or opportunity costs. Careful evaluation is needed for both the industry and for individual enterprises. Nevertheless, sheep are a small but significant producer of greenhouse gases on a national scale (about 3% of the national total) and there could be ongoing pressure to find ways to reduce emissions, particularly if climate changes are more rapid and severe than currently anticipated.

5. Climate change and national and international wool markets/trade

5.1 Implications of climate change for other wool growing nations

This section will focus on the potential effects of climate change on the other two significant wool growing nations – New Zealand and China (International Wool Textile Organisation, 2004).

5.1.1 New Zealand

Climate change projections for New Zealand are similar to those for Australia, with a potential 0.3-1.4 °C average temperature increase by 2030. A stronger westerly airflow is also predicted, with resultant precipitation increases in the west of the country and decreases in the east. There is a likelihood of increased drought frequency due to higher temps, increased evaporation (temperature and wind related) and the possibility of more frequent El Niño events. Eastern New Zealand, which has higher evapo-transpiration rates, will be particularly vulnerable to ENSO-related variability in summer rainfall (Pittock and Wratt, 2001). As with Australia, these climatic changes will have implications for the wool industry in terms of negative effects on growth of pasture and fodder crops, particularly in the drier regions, as well as water availability for stock (although this likely to be less of an issue than in Australia), and introduction and spread of weed species. Higher CO_2 concentrations are likely to offset the impacts of reduced rainfall on pasture and fodder crops (see section 3.1.1), but this effect is likely to drop off as temperatures rise above 2ºC and precipitation is further reduced. There may be some gains (for example, in potential for cold-temperature related stock mortality), with increases in minimum temperatures.

5.1.2 China

Wool production in China falls into both the arid/semi-arid and temperate regions of Asia (Longworth and Brown, 1995; Adger *et al.*, 2001). Climate change scenarios for the 2020s suggest that mean annual temperatures will rise between 1.4 and 1.8 °C in arid/semi arid Asia (with greatest increases in summer) and between 1.1 and 1.5 °C in temperate Asia (with greatest increases in winter). Overall, mean annual precipitation is predicted to increase in both arid/semi-arid and temperate Asia (1.1 to 6% and 0.9-3.9 %). However, summer precipitation in the arid/semi-arid region is predicted to decline by up to 2.1%, leading to severe water stress and possible expansion of deserts (Adger *et al.*, 2001). The latter is likely to accelerate pasture deterioration and land degradation in the pastoral region – two issues that are already affecting wool production in China (Longworth and Brown, 1995). As with Australia and New Zealand, rising CO_2 concentrations are likely to have positive impacts on plant water efficiency and growth (see section 3.1.1), although this will be limited by low soil nutrient levels, particularly in the marginal arid/semi-arid region. The benefits from CO_2 fertilisation would be highest in the temperate region (covering approximately half of China's wool growing areas), coupling, as it would, with the benefits of increasing rainfall. In the semi-arid/arid regions, however, benefits from rising CO_2 concentrations will be offset by the predicted decreases in summer rainfall. Higher CO_2 concentrations will also benefit weed growth. A longer frost-free period may positively affect both pasture and fodder crop growth, as will higher rainfall in the temperate region (Rosenzweigh and Hillel, 1998; Adger *et al.*, 2001). Drought frequency is postulated to increase, associated with rising temperatures and evaporation coupled with increased rainfall variability (Adger *et al.*, 2001). A greater frequency of drought, coupled with pasture deterioration, is likely to put further physiological stress on sheep, a factor that is already adversely affecting the quality of fine wool production in China (Longworth and Brown, 1995). This stress may be alleviated to some degree, however, by higher winter temperatures and lengthening of warm seasons. There is potential, therefore, for an improvement in the fibre quality of Chinese wool, particularly in the temperate regions. Pests and diseases are likely to become more problematic in association with rising temperatures, particularly in relation to pathogen survival over winter (Patterson *et al.*, 1999; Adger *et al.*, 2001).

5.2 National and international consumer issues

Further pressure on the marketability of wool fibre for apparel is likely to occur in the future as climates become hotter and the demand for warm clothing is reduced, particularly in warmer countries like Australia. The demand for coarse wool fibre for interior textiles is less likely to be impacted directly by climate change, although it will remain vulnerable to other market forces. Investigation of alternative uses for fine grade wool, such as the non-woven technology fabrics, would be advisable in light of future climate change scenarios.

Additional pressure may be applied to the wool industry as climate change impacts on the suitability of land for food production. Under future climates, issues of food security, already of concern in relation to population rise and the impacts in developing nations of disease such as HIV/AIDS, (Rosegrant and Cline, 2003), could lead to pressure (both in terms of supply and profitability) to convert land currently under wool production to crops and/or meat production. This will be particularly true for areas where increased rainfall may raise the suitability of land for cropping or where there is competition for dwindling water resources.

6. Synthesis and scenarios

6.1 *Probable interactions between climate change and other issues*

Previous sections have highlighted a wide range of impacts that climate change may have on various aspects of the wool industry, including market, production, natural resource and environmental issues. Over the coming 25 years, climate change is likely to be relatively small, especially comported to inter-annual variation; although there may be disproportionate impacts on the industry due to non-linear bio-physical processes and the relatively small margins in wool production. In addition, there will be substantial changes in market, production, natural resource and environmental issues *independent* of changes in climate. Therefore, it is important to consider the interaction of between climate change impacts and other changes, especially in the light of the interplay between wool, lamb, cattle and crop production. In recent integrated-scenario analyses for Land and Water Australia and the Grains Council of Australia, we identified a range of issues that will be important for agriculture in Australia over the coming 50-100 years (Dunlop *et al*., 2002; Dunlop *et al*., 2003). Similarly, we have explored a range of long term issues affecting the future of production in the rangelands (Foran and Howden, 1999; Howden *et al*., 2002). Below we briefly discuss several such future-issues and how they may interact with climate change to affect the wool industry. The Future Woolscapes Program, through separate consultancies, is identifying issues that could be critical in shaping the future of the wool industry. Once these issues have been collated it will be important to explore their potential impacts in integrated analyses that focus on the interactions between issues including climate change.

6.1.1 Arable land and water resource

Over the last 150 years the area of land used in Australia for crops and sown pasture has increased at about 2% a year, doubling roughly every 35 years (Figure 10; Dunlop *et al*., 2002). The use of water for irrigation and stock has similarly increased continuously over the history of agriculture in Australia. In current agricultural areas these increases cannot continue – there are simply not enough arable land and water resources. The cessation of this increase, when it happens, will be one of the most significant transitions in Australian agriculture. The full ramifications are unknown, but it will almost certainly have significant impacts on broadacre agriculture (see Box below). The impacts of this inherent resource constraint will be greatly magnified by any impacts of climate change that decrease the productivity of land, reduce the availability water resources and increase the demand for water. The wool industry in the high rainfall and wheat-sheep zones could be affected in a number of ways. First, many growers are mixed farmers, so impacts affecting cropping or grazing will affect their businesses. Second, any slowing of agricultural growth, in the crop or sheep sector, will flow on to rural economies with social and economic costs to farmers. Third, future expansions of the cropping sector would be directly at the expense of pasture.

6.1.2 Impact on land use and relative productivities of wool

Modelling by ABARE for the NLWRA suggests that relatively small (1% per annum) changes in total factor productivity (relative to the rest of the world) of alternative broadacre land uses can lead to significant shifts between crop, beef and sheep production over a 20 year period (Walcott, 2001). The area allocated to sheep was most sensitive to changes in the productivity of cropping in the western wheat-sheep zone and beef productivity in the northern wheat-sheep zone. Changes in sheep productivity had relatively little impact in each of the regions, and the areas allocated to sheep were relatively invariant (compared to crop and beef) in the southern wheat-sheep zone and the high rainfall zone. This strongly suggests that impacts of climate change on cropping and beef, both within Australia and in the rest of the world, might be at least as important as the impacts on sheep productivity in determining the land use allocations and wool production in many parts of Australia. Modelling by Howden and Jones (2001) predicts that significant decreases in crop productivity resulting from climate change are very likely in the western wheat-sheep zone. Thus climate change could well lead to significant increases in sheep production in that zone. Howden *et al*. (2001b) found that an increase in CO_2 concentration to 700 ppm, a 3 °C temperature increase and a 10% increase in rainfall (a mid-range climate change scenario for 2100) could lead to a 25% increase in live weight gain of beef in north-east Queensland. Similar beef productivity increases in the northern wheat-sheep zone could lead to elimination of sheep production from that zone. More generally, any changes in the dryer margin of cropping will have impacts on grazing - increases in rainfall will see expansion of cropping into some regions that were previously only suitable for grazing, whereas grazing will inevitably expand in areas that become too dry for cropping.

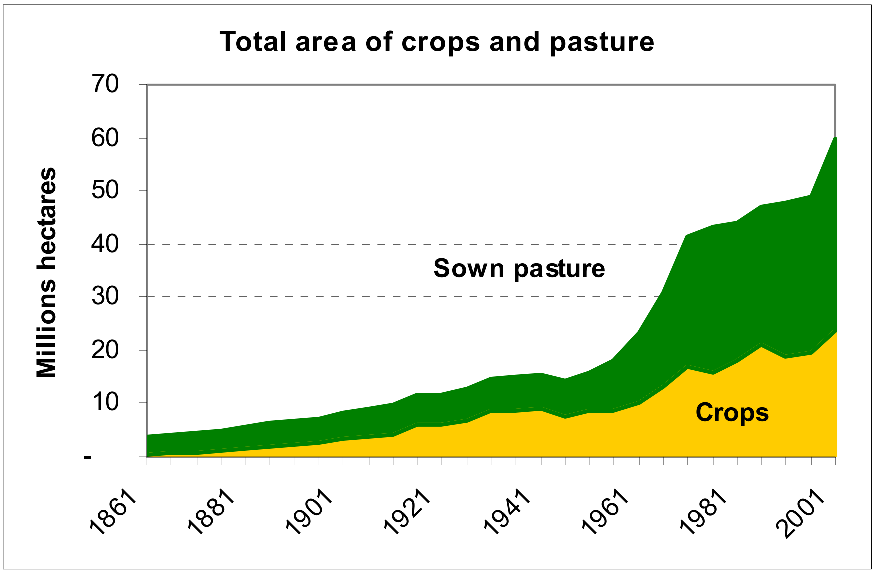

Figure 10. Total area of crops and sown pastures in Australia, 5-year averages 1861-2001.

Box. Two possible impacts of the stabilisation of the area used for crops and sown pastures.
Past area growth has been a considerable component of past growth in agricultural production which has been essential for the maintenance of profitability – future growth will have to come solely from productivity increases and structural changes within agriculture. The past rate of area growth means that, for much of the history of agriculture in Australia, most crop/sown pasture land has been in use less than 35 years, hence it has been relatively unaffected by gradual land degradation processes, like acidification, that take several decades to have significant impacts. Cessation of the continual addition of new land will see the proportion of land that is older, and more degraded, increase considerably.

6.1.3 Farming system developments

Over the next 25 years, developments in farming systems in Australia will also have significant impacts on sheep production. A gradual shifting of the cropping zone and increased water use efficiency are two key examples. Productivity growth and the pursuit of higher yields are likely to see grain production steadily expand into the high rainfall zone, facilitated by the development of new varieties and cropping systems. In many areas this will be directly at the expense of sheep pasture, but it may also see increased availability of feed for higher intensity sheep production (e.g. ultra-fine wool). At the dry margin of the wheatbelt, the imperative for increases in grain yield and productivity could see significant reductions in the area under crop, potentially millions of hectares over the next 50 years, with low intensity sheep grazing the most likely alternative land use. These trends may see land-use pressure on fine wool production but expansion of coarser wool. In addition, developments in farming systems in wheat-sheep and high rainfall zones are seeing advances in water use efficiency of crops and pastures, with concomitant decreases in dam-filling and run-off. In areas without access to aquifers for watering stock, this would have a significant impact on sheep production. Decreased run-off and/or increase evapotranspiration could increase the impacts of these two farming system developments.

6.1.4 Climate variability

Climate variability is a dominant feature of Australian agriculture, affecting both crop and animal production. Recent developments in seasonal forecasting and effective use of that information can significantly reduce the risks associated with climate variability. There is also a growing acceptance that periodic dry years are a natural part of Australia's environment rather than the exception – and that producers should accommodate regular years with low returns in their farm management and business planning. For wool producers this may include storage of feed, preparedness to de-stock early to preserve soil, and delaying restocking to allow good pasture re-establishment after rain, as well as financial management. Climate change will interact with climate variability in two key ways. First, many of the impacts of climate change are likely to be through changes in the extremes of natural variation (hotter peak temperatures and fewer frosts) rather than as a result of changes in average temperatures. Second, climate change models consistently predict that climate variation will increase with climate change. For example, there will be more relatively dry periods and more intense rainfall. This means that in the future, managing climate variability will be more important for managing risks than it has been in the past. In addition, managing for climate variation will better equip producers for adapting to climate change as it occurs.

6.1.5 Production – environment trade-offs

Rural Australia is faced with a wide range of natural resource issues, some affecting production (e.g., weeds and acidification) and others having greater off-site or environmental impacts that may be of more concern to the general community (e.g., salinity and biodiversity loss). There is trade-off between using public NRM resources to fund actions to address these different issues. In the main, actions to address production issues will do little for environmental problems and actions to address the external environmental issues are likely to be at a cost to production. Recognition and management of this trade-off is important for the future development of agriculture. Climate change is likely to interact strongly with both production and environmental NRM issues. For example, weed distributions are likely to change and the migration of biodiversity in response to changing climate will be greatly limited by the paucity of and fragmented nature of remaining native vegetation in most agricultural areas. Growing recognition that climate change is human-caused and that its impacts on biodiversity will be magnified by past human activity could lead to considerable moral pressure and community demand for actions to minimise both the rate of climate change and the impact on species. Extensive revegetation of agricultural land could address both these issues, but would be at a cost to wool production. Note, however, while sheep production may decrease, if appropriately structured, carbon sequestration, biomass production (for bio-fuels) and biodiversity management could provide significant alternative income streams for rural land holders.

6.2 Potential future scenarios and the implications of climate change to these

In this section use a brief scenario analysis to examine the possible impact of climate change on the wool industry.

6.2.1 Scenario analyses

We have developed two baseline scenarios to describe possible trajectories for the industry over the next 25 years based on uncertainty in non-climate-change drivers. We then applied a single set of climate impacts to both scenarios and qualitatively examine the possible impacts of climate change in each. ***It is important to view these scenarios and the impacts as possibilities not predictions and to realise these are preliminary analyses.*** A more detailed scenario analysis could use multiple climate-impact scenarios applied to a number of baseline scenarios that cover production environmental and social dimensions, include regional differentiation, and examine alternative adaptation strategies for each climate-change/baseline scenario combination.

6.2.2 Implications of the scenarios

A number of lessons about the possible impacts of climate change on the wool industry can be drawn from this brief scenario analysis:

- The wool industry will be significantly affected by climate change, but as a whole it is likely to be relatively robust.
- The impacts of climate change on the wool industry may vary considerably depending on the impacts of other drivers of change.
- The impacts are likely to vary among regions and have different impacts on fine and coarse wool production.
- There are likely to be some synergies in managing climate change, e.g. re-vegetation can provide carbon sequestration, biodiversity conservation and shade.
- Early adaptation, e.g. efforts to reduce low emission grazing systems and improved management of climate variation, could significantly reduce the downsides of climate change impacts.

Baseline scenarios	
Scenario 1 Wool remains less profitable than cropping in the wheat-sheep zone; sheep area largely determined by changes in cropping productivity and other land uses; increased cropping intensity and water use efficiency across the wheat-sheep belt; steady expansion of cropping into high rainfall areas and expansion of agroforestry both displacing sheep grazing; reduction in cropping at dryer margin of wheat-sheep belt sees an expansion of sheep grazing.	***Scenario 2*** Wool (and lamb) prices continue their recent increases, increasing the relative profitability of sheep against cropping; cropping intensification reaches a limit with grazing remaining an important part of most crop production systems. Expansions of cropping into higher rainfall areas is very limited, similarly agroforestry remains small scale.

Climate impacts (apply similarly to each baseline scenario)
• Increased awareness of climate change (and its human causes) and need to reduce emissions and minimise impacts on the environment. Pressure increases to reduce emissions from sheep, increase sequestration by pastures and woody vegetation. Similarly there is community pressure to manage impacts of climate change on biodiversity. • There is a general decrease in suitability of dryer areas for cropping and improved conditions for cropping on wetter margins of the wheat belt (although there is much regional variation in these trends). • There is increased impact of weeds (new species/changing distributions, changing competitive relations in sward, increased woody weeds). • Livestock water demand increases, water availability decrease. • There is reduced severe frosts and an increase in frequency of very dry years.

Possible impacts on wool production	
Scenario 1 • Sequestration of carbon through agro-forestry and some woody re-growth in dryer areas retired from cropping help reduce agriculture's greenhouse status. Demand for reduced emissions from sheep is largely met by reduced sheep numbers in most of the wheat-sheep zone and the higher rainfall zone. Re-vegetation for biodiversity conservation under climate change is largely at the expense of pasture. • The shift of cropping into the high rainfall zone is accelerated by climate change in this scenario, with considerable areas of pasture lost and marked reductions in fine wool production. • Pasture condition and animal health are negatively affected as producers lag in their response to the new climatic conditions, especially those focussing on their cropping operations. Ready availability of feed grain and shade from agro-forestry plantings alleviates some of this pressure in the high rainfall zone. • Expanded cropping and increased water use efficiency combine with climate change leading to substantial pressures on water for stock and reduced stream flows. • Fewer sheep and ready supplies of feed-grain make more frequent dry years easier to manage in the high rainfall zone.	***Scenario 2*** • The burden of greenhouse gas mitigation and re-vegetation for biodiversity is shared between cropping and grazing, but does lead to conversion of much pasture. The demand for reduced emissions from sheep places added pressure on wool production. • Some expansion of cropping in the higher rainfall areas is facilitated by climate change. However, the reductions in the area under crop, and expansion of pasture, on the dryer margins are much more significant. • The retained focus on sheep production in farming systems sees faster adaptation to climate change in the management of animal health and pasture. Re-vegetation for mitigation and biodiversity in the high rainfall and wheat-sheep zone provides additional shade. • There are some reductions in water for stock. • Managing more frequent dryer years is an increased challenge.

7. Conclusion: Implications of climate change for the Australian wool industry

The scientific evidence is clear that climate change has already affected Australia and will continue to do so into the future. In terms of the Australian wool industry, this will have likely implications for:

- food resources, with improved pasture/fodder crop growth under higher CO_2 concentrations (and in some areas, higher summer rainfall). This will be generally offset by lower nutrient content and, in some regions, by the impacts of rainfall deficits. Higher drought frequency may also have a negative impact. Pasture composition is also likely to be affected;
- water resources, with decreases in water availability and increased variability in supply;
- wool production and quality, with reduced productivity in marginal areas and possibly some increased productivity in higher rainfall regions, coupled with possible increases in vegetable fault and dust contamination, as well as changes in fibre diameter and strength;
- animal health, with increased thermal stress (particularly in the north) and subsequent increases in animal water demand and susceptibility to pests and diseases (the range of which is also likely to be extended southward), as well as decreased reproductive and growth rates;
- land degradation issues, with greater stress on the land principally brought about by rainfall deficits and increased variability leading to a greater focus on issues of land stewardship;
- competition from other agricultural activities, particularly in regard to cropping and water/land resources (an issue most likely to affect the high rainfall wool growing regions);
- national and international markets, with possible further reductions in demand for apparel wool fibre in response to rising temperatures. International production and supply markets may also shift, with wool growing areas of both New Zealand (western) and China (temperate) likely to be advantaged by climate change, whilst other areas in these countries being disadvantaged (the eastern and semi-arid/arid, regions respectively).

The uncertainty inherent in climate projections and other global change drivers, means that the scale and level of impact of climate change is difficult to quantify. The best adaptation strategy, therefore, is to develop more resilient rangeland systems (including socio-economic and cultural/institutional structures) which are capable of coping with a broad range of possible changes. Existing analyses show, however, that enhanced resilience usually comes with various types of costs or overheads. These vary markedly between systems and perhaps need exploring for different regions where the wool industry operates.

Finally, it must be remembered that the impacts of climate change will come on top of the impacts of other industry pressures (such as changing global markets), and in many cases may not be as important (in isolation) as these issues. However, it has the potential for significant impacts on the Australian wool industry and should be factored into future management plans. Early adaptation strategies, particularly in regard to enhancing resilience, have the potential to significantly reduce the negative impacts of climate change.

8. References

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Appendix 1: 20th century changes in the Earth's atmosphere, climate, and biophysical system

This table provides examples of key observed changes and is not an exhaustive list. It includes both changes attributable to anthropogenic climate change and those that may be caused by natural variations or anthropogenic climate change (Watson, 2001).

Indicator	Observed Changes
Atmospheric concentration of CO_2	280 ppm for the period 1000-1750 to 372 ppm currently (31±4% increase).
Terrestrial biospheric CO_2 exchange	Cumulative source of about 30 Gt C between the years 1800 and 2000; but during the 1990s, a net sink of about 14±7 Gt C.
Atmospheric concentration of CH_4	700 ppb for the period 1000-1750 to 1,750 ppb in year 2000 (151±25%increase).
Atmospheric concentration of N_2O	270 ppb for the period 1000-1750 to 316 ppb in year 2000 (17±5% increase).
Tropospheric concentration of O_3	Increased by 35±15% from the years 1750 to 2000, varies with region.
Stratospheric concentration of O_3	Decreased over the years 1970 to 2000, varies with altitude and latitude.
Atmospheric concentrations of HFCs, PFCs, and SF_6	Increased globally over the last 50 years.
Global mean surface temperature	Increased by 0.6±0.2°C over the 20th century; land areas warmed more than the oceans.
Northern Hemisphere surface temperature	Increased over the 20th century greater than during any other century in the last 1,000 years; 1990s warmest decade of the millennium.
Diurnal surface temperature range	Decreased over the years 1950 to 2000 over land: night time minimum temperatures increased at twice the rate of daytime maximum temperatures.
Hot days / heat index	Increased.
Cold / frost days	Decreased for nearly all land areas during the 20th century.
Continental precipitation	Increased by 5-10% over the 20th century in the Northern Hemisphere, and parts of Australia although decreased in some regions (e.g., north and west Africa, parts of the Mediterranean, south-west Australia).
Heavy precipitation events	Increased at mid- and high northern latitudes and in eastern Australia.
Frequency and severity of drought	Increased summer drying and associated incidence of drought in a few areas. In some regions, such as parts of Asia and Africa, the frequency and intensity of droughts have been observed to increase in recent decades.
Global mean sea level	Increased at an average annual rate of 1 to 2 mm during the 20th century.
Duration of ice cover of rivers and lakes	Decreased by about 2 weeks over the 20th century in mid- and high latitudes of the Northern Hemisphere.
Arctic sea-ice extent and thickness	Thinned by 40% in recent decades in late summer to early autumn and decreased in extent by 10-15% since the 1950s in spring and summer.
Non-polar glaciers	Widespread retreat during the 20th century.
Snow cover	Decreased in area by 10% since global observations became available from satellites in the 1960s. Significant decreases in Australia
Permafrost	Thawed, warmed, and degraded in parts of the polar, sub-polar, and mountainous regions.
El Niño events	Became more frequent, persistent, and intense during the last 20 to 30 years compared to the previous 100 years.
Growing season	Lengthened by about 1 to 4 days per decade during the last 40 years in the Northern Hemisphere, especially at higher latitudes.
Plant and animal ranges	Shifted poleward and up in elevation for plants, insects, birds, and fish.
Breeding, flowering, and migration	Earlier plant flowering, earlier bird arrival, earlier dates of breeding season, and earlier emergence of insects in the Northern Hemisphere.
Coral reef bleaching	Increased frequency, especially during El Niño events.
Weather-related economic losses	Global inflation-adjusted losses rose an order of magnitude over the last 40 years. Part of the observed upward trend is linked to socio-economic factors and part is linked to climatic factors.