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The potential impact of climate change on the Australian wool industry by 2030

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Abstract

By 2030, climate change is likely to have implications for the Australian wool industry, principally through effects on forage and water resources, land carrying capacity and sustainability, animal health, and competition with other sectors, in particular cropping. The nature and scale of these impacts will vary between the wool growing regions, depending on the manifestation of the climate change.

The growth and quality of pasture and fodder crops may be affected by changes in rainfall amounts and variability as well as higher CO_2 concentrations. Water resources in many regions are projected to decrease and become more variable. Animal health is expected to be adversely affected by rising temperatures and a greater incidence and range of pests and diseases. There is likely to be greater stress on the landscape principally brought about by rainfall deficits and increased climatic variability. There is also a strong possibility of increased competition for water and land resources from other agricultural activities, particularly cropping and meat production. The combination of these effects is likely to have an impact on both wool production and quality, with reduced productivity in marginal areas, possibly increased productivity in higher rainfall regions, increases in vegetable fault and dust contamination and changes in mean fibre diameter and staple strength. National and international markets could also be affected, with reductions in demand for apparel wool fibre in response to a more temperate climate. International production and supply markets might also shift, with the wetter

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wool growing areas of both New Zealand and China potentially being advantaged by climate change, and the drier wool regions of these countries being disadvantaged.

A preliminary qualitative scenario analysis suggests that although the wool industry will be significantly affected by climate change, as a whole it is likely to be relatively robust to it. Early adaptation, for example through efforts to produce low emission grazing systems, more sustainable management especially in the rangelands, and improved management of the effects of climate variation, could significantly reduce the downsides of climate change impacts.

Keywords: Climate change; Australian wool industry

1. Introduction

There is strong evidence that human activities have significantly increased the Earth's atmospheric concentrations of greenhouse gases and aerosols and in turn affected global climates (Houghton et al., 2001). For example, indications are that the increase in surface temperature over the 20th century, with the 1990s being the warmest decade in the instrumental record (1861–2001), is likely to have been greater than that for any other century in the last thousand years (Mann et al., 1998; Houghton et al., 2001). Such trends of climatic change will continue into the future due to the greenhouse gases already accumulated in the atmosphere, and are likely to be substantially exacerbated by further greenhouse gas emissions (Houghton et al., 2001).

Although climate change is just one factor that could affect Australian agriculture in the future, it is likely to increase the vulnerability of the sector to biophysical and economic stresses. This is particularly true of the potential effects of climate change on water demand and supply brought about by the combination of warming, increased potential evaporation and reductions in rainfall. Possible increases in drought frequency and severity are likely to provide additional stresses (Pittock, 2003).

The wool industry comprises 7–10% of the gross value of agricultural production in Australia, earning between three and four billion dollars in export income per annum (Ashton et al., 2000; Shafron et al., 2002). Australia's sheep flock is contained in three zones (Fig. 1) – the wheat-sheep zone (55%), the high rainfall zone (33%) and the pastoral zone (12%) – with specialist wool producing farms accounting for 32% of Australia's wool output (Shafron et al., 2002; Australian Wool Innovation Limited, 2004). The fine wool (<18.5 μm) proportion of the Australian clip has increased from 8.8% in the early 1990s to 30% in 2003 (Australian Wool Innovation Limited, 2004). Recently there has been a decline in global wool consumption brought about by a number of factors, including competition from other fibres and changing consumer tastes (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. Despite the reduction in production and in prices, wool remains an important component of Australian farm incomes (Shafron et al., 2002).

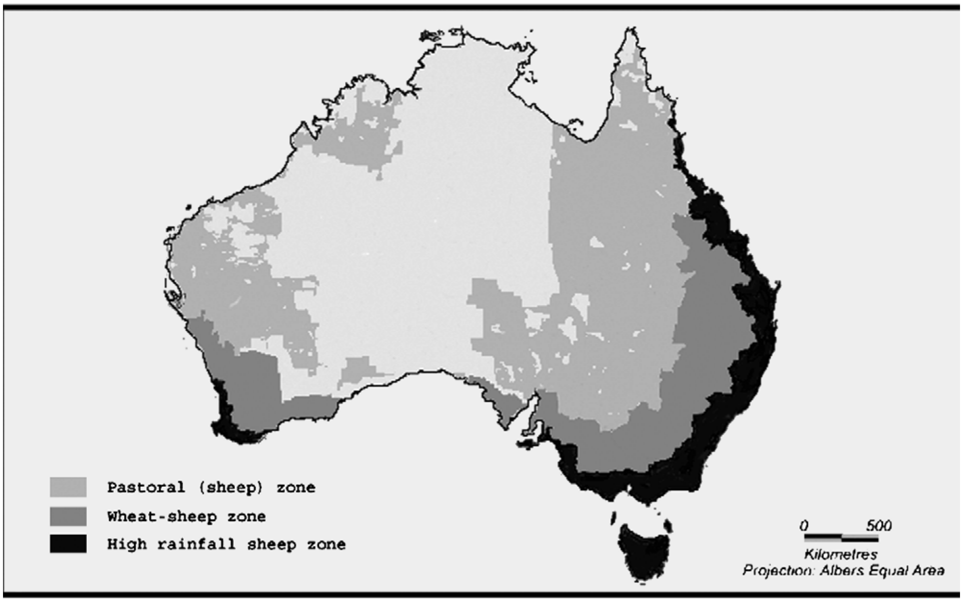

Fig. 1. Sheep producing zones in Australia (adapted from Australian Natural Resources Atlas).

As one of Australia's significant agricultural industries the prospective effect of climate change on wool growing is of some concern, particularly when coupled with other drivers of change such as: the relative profitability of sheep production and alternative land uses, government policy, and condition of the natural resource base. Utilising climate change scenarios for 2030, this paper presents a review of the potential effects of climate change on wool growing in Australia. It focuses on effects on pasture and fodder crops, wool production and quality, animal health and reproduction, water availability and demand, land stewardship and sustainability and national and international consumer issues. In the final section of this paper we use a qualitative scenario approach to illustrate the interaction of future climate-change and other drivers on the Australian wool industry.

2. Climate change scenarios for 2030

The Intergovernmental Panel on Climate Change (IPCC) projections for the concentration of atmospheric CO_2 in the year 2030 range from 400 to 480 ppm, compared to about 280 ppm in the pre-industrial era and about 372 ppm currently (Houghton et al., 2001). The breadth of this range is the result of uncertainties associated with different socio-economic assumptions in greenhouse gas emission scenarios (demographic, social, economic, and technological) as well as those associated with modelling the persistence of the present removal processes (carbon sinks) and the magnitude of climate feedback on the terrestrial biosphere.

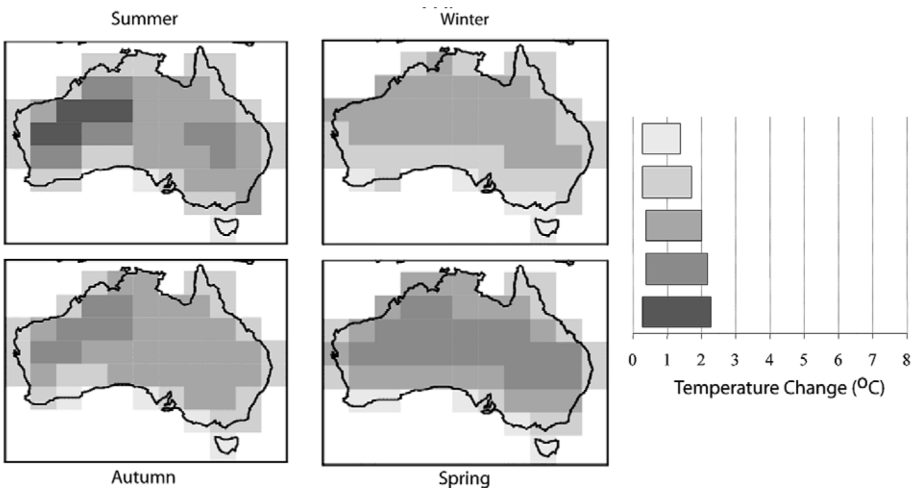

Fig. 2. Average seasonal warming ranges (°C) for around 2030 relative to 1990. The bars show ranges of change for areas with corresponding greyscales on the map. Ranges are due to model and emissions uncertainty (adapted from CSIRO, 2001).

The implications for such changes for Australian temperatures and rainfall are shown in Fig. 2 and Table 1. The ranges in the projections are related to the uncertainties described above. 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 high rainfall sheep zone to ±5% in the northern pastoral zone (see Table 1). The most pronounced decreases are predicted for winter and spring, although some coastal areas of the high rainfall sheep zone may become wetter in summer, and some areas of the eastern wheat-sheep zone may become 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 frequency of El Niño events may be increased by global warming. However, most of the models simulate more frequent heavy rainfall events and flooding in those areas where average rainfall increases or slightly decreases, but 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).

In each region and each season the ranges of possible change in rainfall include both increases and decreases, with up to a 30% variation (e.g., −15% to +15%). Obviously, such uncertainty is challenging for industry planning and adaptation.

Table 1
Predicted ranges of seasonal rainfall change for 2030 for the Australian wool growing zones (E = east, N = north, W = west, S = south. QLD = Queensland, SA = South Australia, VIC = Victoria, Tas = Tasmania)

Season	Wool growing zones		
	High Rainfall	Wheat-Sheep	Pastoral
Summer	−5 to +15% in E (coast)	±15% in NE and E and parts of SW	most areas ±15%
	±15% in parts of E and SE	−15 to +20% in SE	areas of ±15% in N
	−15 to +5% in NE QLD, W VIC and TAS	±20 in SW	−5 to +20% in S
	−20 to +5% in far SW		−5 to +15% in central N
Autumn	±15% in E	in from range c to −5 to +15% in E and S	−5 to +15% in E
	−15 to +5% in SE	−15 to +5% in S (SA)	−15 to +5% in central area
	−20 to +5% in SW	areas of ±15% in S and SE	−15 to +5% in coastal area in central N and S, and inland
Winter	−15 to +5% in S, SE and far NE areas	−15 to +5% in S, SE and far NE areas	no predictions for central, N and W areas
	±15% in NE	±15% in NE	±15% in S and NE
	−20 to +5% in SW	−20 to +5% in SW	−15 to +5% in SE
	−5 to +15% in TAS		−20 to +5% in SW
Spring	most of area −15 to +5%	−15 to +5% in SE, E and NE	no predictions for NW and parts of central
	−20 to +5% in SW and SE QLD	−20 to +5% in SW and S (SA)	−15 to +5% in E and central N
			±15% on N coast and central S
			−20 to +5% in SW

Ranges are due to model and emissions uncertainty. Information derived from http://www.cmar.csiro.au/e-print/open/projections2001.pdf.

3. Impacts of climate change on the Australian wool industry

Climate change is likely to affect a range of factors associated with wool production. These include pasture and fodder crops, the quality and quantity of wool production, animal health and reproduction, and water availability and demand. The following sections focus on the direct impacts of climate change on various aspects of the wool industry.

3.1. Impact on pasture and fodder crops

The impact of climate change on pastures and fodder crops is likely to vary between geographic and agro-ecological systems because of the expected differences in the nature of climate change between regions. Furthermore, the uncertainty concerning the direction and magnitude of changes in climate means the exact effect on pastures is unclear. It is probable that in 2030 the impacts of climate change will be noticeable, although not dramatic and will be largely manifested through changes in pasture growth and quality 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. It is worth noting, however, that these studies are often preliminary and/or are based on non-Australian ecosystems. There is a clear need, therefore, for further research to evaluate the potential effects of future CO_2 and climate change on Australian grazing systems, such as the free-air CO_2 enrichment experiments currently being carried out in Queensland and Tasmania (Stokes et al., 2005; Hovenden et al., 2006). Nevertheless, using the literature available it is possible to explore the potential effects of climate change. This is done in the following sections in relation to the pastoral, wheat-sheep and high rainfall sheep producing regions (zones) of Australia (see Fig. 1).

3.1.1. Pasture productivity

Experimental evidence from a number of studies indicates that elevated concentrations of atmospheric CO_2 increase the rate of photosynthetic carbon assimilation in plants (see Wand et al., 1999 and Nowak et al., 2004 for overviews). This effect, frequently referred to as CO_2 fertilisation, has been found to apply to both C_3 plants (e.g. trees, forbs and temperate grasses) and C_4 plants (e.g. tropical grasses), although responses vary between species and tend to be smaller in C_4 species (Wand et al., 1999; Campbell et al., 2000; Ghannoum et al., 2001). In general, the effect appears to plateau as CO_2 concentrations rise above 500 to 600 ppm (Allen et al., 1996).

Elevated CO_2 has also been demonstrated to decrease stomatal conductance and leaf transpiration, thus increasing the water use efficiency of plants and in turn the effective soil water content (Volk et al., 2000). This increase in efficiency in the conversion of water into dry mass has been shown to raise above ground and, in some cases, below ground plant productivity (Wand et al., 1999; Arnone et al., 2000; Pritchard and Rogers, 2000; Poorter, 1993). For example, it has been estimated that the elevation of CO_2 concentrations to 700 ppm could increase plant productivity by 10 to 15% in mesic environments and 20 to 40% in water-limited situations (Wand et al., 1999). In water-limited conditions, such as experienced in much of Australia's rangelands, the main benefit of increased levels of CO_2 is derived through the interaction of plant water use efficiency and soil moisture. It has been projected that the combination of these effects under enhanced CO_2 conditions will improve the ability of plants to withstand the stresses associated with reduced rainfall, (e.g. Adam et al., 2000; Ghannoum et al., 2001), although this will vary with species and soil conditions (Clark et al., 1999; van Ittersum et al., 2003). In terms of pasture growth, Stokes et al. (2003) suggest that under elevated CO_2, the moisture-CO_2 interactions may buffer the effects of inter-annual variation in rainfall on grass production.

Plant growth response to elevated CO_2 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; Luo et al., 2004). For example, Greer et al. (2000) demonstrated that rising air temperature enhanced the effects of elevated

CO_2 on the growth response of five C_3 temperate pasture species (*Festuca arundinaceae, Lolium perenne, Phalaris aquatica, Trifolium repens* and *Poa annua*). In contrast, studies into the effects on crop yields of rising temperature in isolation of changes in CO_2 indicate that temperature increases above 3 °C caused crop yields to fall (Wang et al., 1992; van Ittersum et al., 2003). There is also some evidence that for grasslands and crops conditions of elevated CO_2 can enhance above-ground primary productivity, even where there are initial decreases in precipitation, through the benefits of increasing water-use efficiency (Nowak et al., 2004). However, the degree to which elevated CO_2 is likely to affect water-use efficiency in grasslands has been shown to vary across ecosystems, with the baseline influence of water dynamics on the grasslands playing a strong role (Morgan et al., 2004). For example, studies have shown that grasslands strongly influenced by seasonal water dynamics (such as some native grasslands) are more likely to experience enhanced biomass in response to elevated CO_2, particularly during dry years (Morgan et al., 2004). However, where water availability is particularly limiting, such as in some semi-arid ecosystems, the effects of CO_2 on soil water dynamics may not be detectable (Nowak et al., 2004). Indeed, studies suggest that beyond a threshold of between 300 and 500 mm precipitation/year further decreases in precipitation can offset the positive effects of enhanced CO_2 conditions on plant growth (Clark et al., 1999; van Ittersum et al., 2003; Nowak et al., 2004). Similarly, low nutrient availability can limit the response of plant productivity to raised CO_2 (van Ittersum et al., 2003; Nowak et al., 2004), although there is some debate over the response of slow growing species and nutrient-stressed plants (see Poorter, 1998; Lloyd and Farquhar, 2000). There is also some indication that nitrogen availability can become increasingly limited through time, with nitrogen being sequestered in greater amounts where there is increased biomass as a result of elevated CO_2 (Luo et al., 2004). The effect of CO_2 on plant growth can also be related to the seasonality of the rainfall. For example, studies suggest that grasslands growing in Mediterranean climates (with a single dry period at the end of the growing season) are more likely to experience CO_2 driven water relations benefit near the end of the growing season, whereas grasslands with multiple in-season wet/dry cycles appear to benefit more consistently (and substantially) throughout the growing season (Morgan et al., 2004).

Evidence suggests that elevated CO_2 may affect not only individual plant species but also community composition through avenues such as differentially affecting the survival, vegetative growth, seed production and seedling recruitment of some species (Clark et al., 1997; Bond and Midgley, 2000; Edwards et al., 2001). It has been argued that higher levels of CO_2 could lead to the expansion and thickening of woody plants in grass-dominated ecosystems (Archer et al., 1995; Bond and Midgley, 2000). The potential invasion of pasture by trees and woody shrubs has obvious implications for grazing value (Campbell et al., 2000). 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). Such an expansion could reduce pasture production, impede stock access to water points and increase mustering costs and soil erosion. Possible management strategies include the use of fire to control woody plant establishment under elevated CO_2 concentrations (Howden et al., 2001a).

In Australia, there are likely to be north–south differences in the response of pasture production to climate change, as well as differences between the pastoral, wheat-sheep and high rainfall sheep zones. For example, Crimp et al. (1999) suggested that a lengthening of the growing season due to higher winter minimum temperatures and humidity in Queensland's grazing lands (where pasture growth is currently limited by winter minimum temperatures) could result in an increase in pasture growth if nutrients are not limiting, especially where dominated by C_4 grasses. However, under warmer climates with higher concentrations of CO_2 the suitability of pasture for sheep could be limited in eastern Queensland by the expansion of black speargrass, in the north by the presence of tropical tall grass pastures, and in the west by variable and low pasture production (Hall et al., 1998). Indeed, the climate change scenarios for many areas of the pastoral sheep zone are for marked reductions in rainfall and increased inter-annual variability associated with the El Niño-Southern Oscillation. A consequence will be lower and more variable pasture production, since the reduction in rainfall will exceed the level at which increased CO_2 can buffer declines in growth (Crimp et al., 2003).

In contrast, for many southern farming regions (including the high rainfall and wheat-sheep zones) 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. (2001a) elevated CO_2 and warming (+3 °C) improved herbage yield of mixed sub-clover (*Trifolium subterraneum*) 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 and other legumes in pastures. In addition, there may be greater opportunity for summer-growing forage species in some areas.

In the southern pastoral sheep zone important C_4 shrub species, such as *Atriplex vesicaria* (bladder saltbush), 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 (Burbidge, 1945). A consequence could be the contraction of the distribution of the shrub.

Early expectations were that shifts in the distribution of native C_3 and C_4 grasses were possible in the pastoral and wheat-sheep zones 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 cause a decline in the quality of pastures for livestock production because the former tend to contain less protein, more lignin and less easily digested nutrients than the latter. 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.

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. This is discussed in more detail later.

3.1.2. Nutritive value

Under future climate change there may be changes in the nutrient value of both native pastures in the pastoral and wheat-sheep zones and in sown pastures in the wheat-sheep and high rainfall zones. For example, experiments indicate that under conditions of elevated CO_2 there are decreases in leaf nitrogen content (Zanetti et al., 1997; Luo et al., 1994; Lilley et al., 2001b) and increases in non-structural carbohydrate content (Poorter et al., 1997; Lilley et al., 2001b) for pasture species. These shifts in nitrogen and carbohydrate content do not appear to significantly affect the digestibility of the species thus far studied (Lilley et al., 2001b). Indeed, Lilley et al. (2001b) argue that increased levels of non-structural carbohydrates in pasture in response to increases in CO_2 concentrations could lead to better utilization of nitrogen in the rumen and thus enhance livestock performance.

The combined effect of CO_2 and temperature increases appears to vary with species and plant functional group (Poorter et al., 1997; Lilley et al., 2001b; Reich et al., 2001). In a study on the effects of climate change on the nutritive value of grass-legume pastures (viz. *Phalaris* and *Trifolium*) of south-eastern Australia, Lilley et al. (2001b) concluded that nitrogen concentrations in the cut biomass would be unaffected by warming but decreased by elevated CO_2, whilst non-structural carbohydrates would be increased by elevated CO_2 and decreased by warming, although the latter would be complicated by interactions with radiation, soil water status and photo-period. They argued, however, that the overall combined effect of warming and elevated CO_2 on grass-legume pastures in southern Australia would be to raise the herbage nutritive value and digestibility. In contrast, Wilson (1982) suggested that warming would significantly decrease the non-structural carbohydrate concentrations and digestibility of tropical forage species. It is likely, therefore, that the implications of climate change on the nutritive value of pastures will vary between production systems. In those regions with forage high in nitrogen, such as temperate pastures in the wheat-sheep and southern high rainfall zones, there is generally more protein content than can be usefully consumed by stock. Any reduction in leaf nitrogen content in these zones under higher levels of CO_2 is therefore less likely to impact on overall nutritive values. In contrast, elevated CO_2 concentrations coupled with warming may exacerbate nutrient deficiencies in those systems which are already deficient in nitrogen, such as experienced by much of the northern pastoral zone for part of the year (Scholes and Howden, 2003).

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, a study by Jolly and Lyne (1970) indicated that an increase in subdermal temperature of 5 °C from current levels resulted in increased wool growth, but if the temperature was further increased, wool growth declined and then ceased.

There is little data specifically on the implications of climate and pasture change for wool and sheep production. Most 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. For example, Hall et al. (1998) found that safe carrying capacities and live weight gain of cattle in the Queensland rangelands would be increased under climate change. They determined that safe carrying capacities would be increased between 7% and 27% for beef properties in parts of Queensland, such as the south-east. This was due to warmer temperatures, with the magnitude of response dependent upon the concomitant changes in rainfall (from −10 to +10%). 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, an increase in rainfall would produce an equivalent increase in carrying capacity. Both increases in temperature (3 °C) and a doubling of CO_2 alone were found to increase carrying capacity by as much as 30% and 14% respectively. In other regions higher temperatures had a negative effect on safe carrying capacity. 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.

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 could 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 on the face of it this may be a desirable outcome, it may be accompanied by a rise in the incidence of tender wool as the variation in forage availability and quality becomes greater between seasons. In general, effects on staple strength could include both increases and decreases depending on the location and the nature of climate changes actually experienced. Furthermore, ewes experiencing low feed intake during gestation (particularly during the last six weeks of pregnancy) produce lambs in which secondary follicle production has been impaired. Such an impairment has consequences for long-term wool production (Entwistle, 1974). Low feed intake can also induce follicle impairment in lambs (Schinckel and Short, 1961).

Increased vegetable fault may occur in areas with improved pasture yields or if there is a change in pasture composition (e.g. increases in grass or legume components that lead to more grass seeds or medic burrs). This is likely to have consequences for clean wool yield, but more importantly for prices due to increased costs for removal of vegetable matter during the scouring, carding and gilling processes. It is also possible that dust contamination of the fleece will increase in those regions where reduced rainfall or greater inter-annual variation in rainfall results in an enhanced risk of land degradation and erosion (Crimp et al., 2003). This could lead to a rise in the amount of noil (short or knotted fibres that are separated from the long fibres by combing) produced during the carding process and in turn reduce the fibre length and spinning quality of the wool.

Whether changes in climatic conditions would dictate a change in the preferred breed or strain of sheep is not clear. The sheep industry is currently undergoing major breed adjustments, including the introduction of a number of new breeds. Concerns have already been expressed over the decline in numbers of merino ewes below sustainability levels (John Ive, *pers. comm.)* Given that the quality of coarser wool is less vulnerable to the impact of drier conditions than finer wools, and would therefore incur relatively less price discount if rainfall declined, one possibility is that there would be a displacement of finer-woolled sheep by stronger woolled merinos. However, such a shift to production of coarser wools would run counter to industry efforts to produce higher value finer wool for apparel, would result in a drop in wool incomes, and would have Australia competing more directly with New Zealand.

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, including via nutrition. 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 (Howden et al., 1999b). This is likely to 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. For example, Howden and Turnpenny (1997), using a THI threshold of 80, calculated that there has already been a significant increase (60%) in the incidence of stress days in Gayndah (central east Queensland) over the last 40 years and that there would be a 138% increase over the next 100 years under mid-range climate change scenarios. Such increases in thermal stress could reduce animal productivity through lower growth rates due to appetite suppression (Alexander and Williams, 1973; Silanikove, 1987; West et al., 1991), decrease reproductive rates (see Section 3.3.3), and increase concerns about animal welfare in intensive livestock handling activities, such as live sheep exports (Howden et al., 1999b). 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 (Finch et al., 1982) means that the search for effective adaptation options will be challenging. In contrast, higher minimum temperatures may result in a reduction in the frequency and severity of cold-stress events, such as conditions that foster high lamb mortality and post-shearing losses.

3.3.2. Pests and diseases

The potential exists for the health of sheep to be adversely affected by climate change due to an anticipated increase in the 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 distribution of the insect vector of blue-tongue disease in Australia, *Culicoides wadia*. Its current limit is the north coast of New South Wales, but in future it may extend over the entire New South Wales coast and permanently establish in South Australia and Western Australia (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 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. In addition, other insects could become more abundant. For example the bush tick (*Haemaphysalis longicornis)* may spread southwards (Sutherst, 1990). Internal parasites, such as Barbers Pole, which thrive in warm and moist conditions (Cole, 1986) could increase in numbers where conditions become warmer and wetter. Other parasites, particularly those dependent on temperate and/or wet conditions, could become less prevalent where conditions become drier and hotter. For example, the distribution of the liver fluke (*Fasciola hepatica*) is dependent on an aquatic snail (*Lymnaea tomentose*; Cole, 1986), which could become limited in the future by a reduction in runoff to creeks, swamps and areas susceptible to water logging. Lice and keds are also expected to decline with global warming (Sutherst, 1990). Pest and parasite abundance could also become more variable in response to heightened variation between seasons. Parasites may appear earlier in the season and go through more generations each year. How afflictions such as ovine Johne's Disease 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 a greater susceptibility 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 pastoral zone indicate that heat stress is a major factor in lowering reproductive performance. Heat stress can reduce ram fertility (which is linked to increased failure of fertilisation due to defective gametes) and increase neo-natal mortality in lambs (Entwistle, 1974). 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, although such use will be governed by questions of cost effectiveness and logistics of application.

Sheep that are poorly adapted to heat stress suffer increased levels of embryonic mortality and reduced foetal growth when exposed to continuously hot conditions. On the other hand, ewes acclimatised to high temperatures and subjected to diurnally fluctuating temperatures exhibit no such effects (Ryle, 1961; McCrabb et al., 1993a,b). Mortality in lambs produced by ewes experiencing heat stress is higher than in lambs produced during cooler conditions (Alexander and Williams, 1973).

Changes to pasture availability and quality may also affect the reproduction of sheep. For example, reduced nutrition in the last 6 weeks of pregnancy, such as caused by a lack of green herbage under drought conditions, can result in an increased incidence of pregnancy toxaemia (Charismiadou et al., 2000), particularly in ewes bearing twin lambs. Changes in feed supply can also affect ewe weights and in turn ovulation rates and reproductive performance (Killeen, 1967; Fletcher, 1971).

The combination of lower reproductive rates, poorer growth and survival of lambs and reduced growth of adult sheep has the potential for making some areas where sheep are currently run 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). Rising temperatures in the future have the potential to exacerbate this situation, not only in the regions already affected but also in regions currently unaffected or only minimally affected (particularly in the northern pastoral zone). Reproductive issues associated with poor pasture nutrition are also likely to increase as the incidence of drought rises. Possible management strategies could include: stronger selection for plain-bodied sheep (which are more tolerant of heat than wrinkly ones and are consequently more robust in terms of reproduction); preferential supplementary feeding; ultrasonic scanning of ewes during pregnancy to provide targeted supplementation or other beneficial management; and where appropriate, shift mating time to ensure that lambing coincides with peak forage availability (i.e. later winter–spring).

3.4. Impact on water availability and demand

Climate change is likely to affect water resources by increasing the demand for water, changing surface water and streamflow regimes (e.g. flooding), and through possible effects on groundwater, such as depth to the water table 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 in southeast Queensland are likely to increase by around 13% with a temperature increase of 2.7 °C, with further non-linear increases as temperatures continue to rise. Higher water use rates by livestock mean that they will be unable to travel as far from watering points, limiting use of resources in extensive grazing operations and tending to increase grazing pressure near watering points. This in turn could contribute to land degradation in the pastoral and wheat-sheep zones.

Reductions in rainfall across much of southern Australia and increases in evaporation rates may combine to make surface water less abundant in many grazing lands (particularly in the wheat-sheep and pastoral zones) 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 (12–35%) expected over the Murray-Darling Basin by the year 2050. However, Arnell (1999) also noted that potential increases in rainfall intensity could raise the chance of flood conditions, which would also increase the chance for runoff conditions to fill on-farm water storages. Higher temperatures and lower flows may also increase blue-green algae blooms (Viney et al., 2003) and also potentially increase salt concentrations. The latter would in turn raise the water requirements of stock.

The implications of climate change for groundwater are uncertain and are likely to vary markedly from place to place, depending on the rate 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, the elevation of atmospheric CO_2 levels to those predicted for 2030 (400–480 ppm) will increase groundwater recharge if there are no alterations in climate, and if there is no increase in plant biomass to re-equilibrate overall water use (van Ittersum et al., 2003). This is due to the effect of increased atmospheric CO_2 on the stomatal aperture of plants, restricting transpiration per unit of leaf area. Where low soil nutrient levels limit plant growth, the effect could be enhanced, especially where increases in rainfall occur (Morgan et al., 2004). However, if there are significant reductions in rainfall from climate change, any positive effects of increased CO_2 will be over-ridden and reductions in recharge may occur. Such a reduction could also occur with increased temperatures where soil nutrient levels are not limiting (van Ittersum et al., 2003).

3.5. Impact on land degradation

There is a strong possibility that climate change will exacerbate a number of types of land degradation. For example, where rainfall is significantly reduced plant cover is negatively affected and grazing lands become more susceptible to soil erosion. This process serves to reduce pasture productivity through loss of valuable soil nutrients (McKeon and Hall, 2000). Erosion may also be an issue where there are increases in extreme daily rainfall events, particularly in areas where reductions in annual rainfall amounts have negatively impacted on vegetation cover. Such projections have been made for much of southern Australia (CSIRO, 2001). In addition, climate models suggest there may be increases in storm frequency and intensity under future climate change, although there is some level of uncertainty attached (Abbs and McInnes, 2004; Walsh et al., 2004). If realised, such a trend could result in higher levels of wind and water erosion.

Climate change may also have an impact on dryland salinity. The area at risk of dryland salinity could increase in regions where rainfall increases under future climate change, particularly when combined with the effect of elevated atmospheric CO_2 (see section above). However, the risk of dryland salinity could be reduced where there are significant reductions in rainfall under future climate change.

4. Probable interactions between climate change and other issues

Over the coming 25 years, climate change is likely to be relatively small, especially compared with inter-annual variation, although there may be disproportionate impacts on the industry due to non-linear bio-physical processes and the relatively small financial 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 climate change impacts and other changes, especially in the light of the interplay between wool, crop and meat (lamb and beef) production. Below we briefly discuss several such future-issues and how they may interact with climate change to affect the wool industry.

4.1. 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 normal part of Australia's environment rather than the exception, and that producers should accommodate regular years with low returns within their farm management and business plans. For wool producers this may include storage of feed, preparedness to de-stock early to protect pasture species and preserve soil, and delaying restocking to allow good pasture re-establishment after rain. Good financial management is also important. 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 (higher peak temperatures and fewer frosts) rather than as a result of changes in average temperatures. Second, climate change models predict that climate variation will increase with climate change, with more dry periods where average rainfall is predicted to decrease, and more extremely wet years where average rainfall is predicted to increase (CSIRO, 2001). 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, although it should be noted that current tools for dealing with climate variability are largely based on correlative/empirical 'predictions' that may not hold up under future climate change. Recent advances in dealing with climate variability, therefore, could be lost at the same time as the need for such tools increases.

4.2. 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 (Fig. 3; Dunlop et al., 2002). The use of water for irrigation and livestock 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. 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, about half of the crop/sown pasture land has been in use 35 years or less (Fig. 3), 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 to the agricultural estate will see the proportion of agricultural land that is older, and more degraded, increase considerably. The impacts of this inherent resource constraint will be greatly magnified by any influence of climate change in decreasing the productivity of land, reducing the availability of water resources and increasing 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 on land or water availability that affect either cropping or grazing will affect their businesses. Second, any slowing of agricultural growth due to lack of additional resource availability, in the crop or sheep sector, will flow on to rural economies with social and economic costs to farmers and their communities. Third, any future

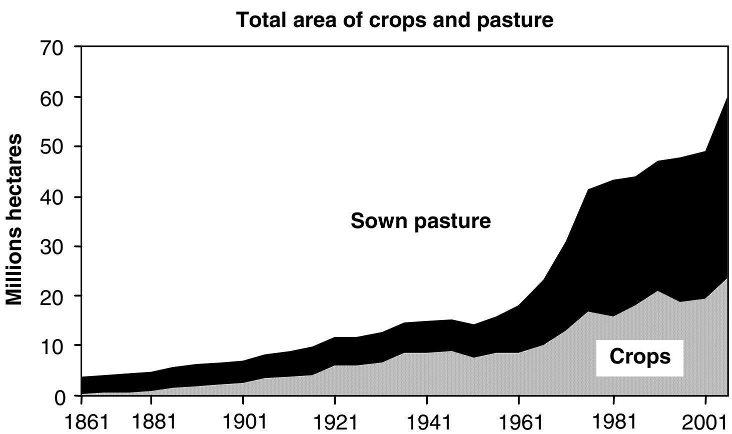

Fig. 3. Total area of crops and sown pastures in Australia, 5-year averages 1861–2001.

expansions of the cropping sector would be directly at the expense of improved pasture.

4.3. Impact on land use and relative productivities of wool

Wool production is an element in a dynamic between the production of various crops and animal products including beef and lambs, hence changes in the production factors or profitability of these other activities are likely to affect the wool industry. Modelling by the Australian Bureau of Agricultural and Resource Economics 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 in that study 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 direct climate change impacts on sheep productivity in determining the land use allocations and wool production in many parts of Australia.

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). On the other hand, modelling by Luo et al. (2003) predicts that significant decreases in wheat yields and grain nitrogen content resulting from climate change are very likely in the southern wheat-sheep zone. If this effect is consistent across the wheat-sheep zone, it could well lead to significant increases in the land available for sheep production in this zone. More generally, any changes in the drier 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 (even though grazing productivity may also be decreased). In addition, advances in the water-use efficiency of crops and pastures could see decreases in dam-filling and run-off in the wheat-sheep and high rainfall zones. In areas without access to aquifers for watering stock, this would have a significant impact on sheep production.

Additional pressure may be applied to the wool industry as climate change impacts on the suitability of land for food production. Issues of economic return and food security, the latter already of concern in relation to population rise (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 (beef and lamb) production. For example, 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 central Queensland. Similar beef productivity increases in the northern wheat-sheep zone could lead to elimination of sheep production for wool from that zone.

Overall, these trends may see land-use pressure on fine wool production but expansion of coarser wool production. However, further research is needed in order to understand the extent to which competition between the wool and prime lamb industries would affect the relative productivity of wool under climate change scenarios. Such research should ideally integrate climate change with factors such as market influences and socio-economic dynamics and explore scenarios of crop-livestock rotation, pasture, and crop and flock composition.

4.4. 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). Climate change is likely to interact strongly with both production and environmental natural resource management 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 human activities are contributing to and accelerating climate 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 native species. Extensive revegetation of agricultural land could address both these issues, but would reduce the area available for wool production. Note, however, while wool 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.

4.5. Greenhouse gas emissions and sinks

As the effects of human-induced climate change become more obvious, there is likely to be increasing pressure to identify ways to reduce greenhouse gas emissions. Sheep are a small but significant producer of greenhouse gases (especially methane) on a national scale (about 3% of the national total) and are the second highest emitters by livestock type (National Greenhouse Gas Inventory, 2003). The emissions of methane and nitrous oxide are effectively an unavoidable aspect of grazing livestock, constituting a major proportion of greenhouse gases from terrestrial ecosystems (Mosier, 2001; Neufeldt et al., 2006). Carbon release or storage from woody plants and soils can constitute a large flux of greenhouse gases under situations such as fires, land clearing, soil degradation and accumulation of plant biomass. For example, pastures that are being invaded by woody weeds are likely to be storing substantial amounts of carbon over a period of decades before they cease accumulating biomass (Moore et al., 2001).

The Kyoto Protocol, which has recently come into force but has not been ratified by Australia, allows nations to include grazing land management as an 'Additional Activity' for carbon sink management. Whilst the land used by the wool industry could feasibly be a large sink for carbon overall, it will probably be a small sink on a per hectare basis (Scholes and Howden, 2003). This is likely to raise the cost of monitoring and verification relative to any financial benefit from establishing a carbon sink. Initial studies have shown that the extent of any financial gain from reducing greenhouse gas emissions through management of pasture quality and stocking rates is dependent on specific situations, such as the initial land condition (Howden et al., 2003). In the few examples analysed so far, there appear to be more cost-effective means of reducing net greenhouse gas emissions than storage. Careful evaluation is needed, therefore, for both the industry and for individual enterprises.

4.6. National and international markets

Climate change is also likely to have implications for both national and international wool markets. Public perception and international trade are likely to be important components, with the latter being influenced by the effect of climate change on other wool producing nations.

4.6.1. 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 warmer and the demand for cold-weather clothing is reduced, particularly in warmer countries like Australia. The demand for coarse wool fibre for interior textiles is less likely to be affected directly by climate change, although it will probably remain vulnerable to other market forces. Investment in alternative, high-return uses for fine wool, such as the non-woven technology fabrics, would be advisable in light of future climate change scenarios. This is particularly pertinent in the light of increasing pressure on the apparel wool market from alternative fibres, in particular synthetic fibres – the demand for which is unlikely to be affected by climate change.

4.6.2. Implications of climate change for other major wool growing nations

The leading wool producing nations are Australia, New Zealand and China, with Australia being the leading producer of fine wool, New Zealand the leading producer of coarse (strong) wool and China producing both fine and coarse wool. China is also the highest international importer of Australian wool (Zhang, 1990; International Wool Textile Organisation, 2004). Currently only a relatively small proportion of New Zealand wool production is marketed in direct competition with Australian wool. Overall, any effects of climate change on the Chinese and New Zealand wool industries is likely to have the most implications for the Australian wool industry.

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. Precipitation is expected to increase in the west of the country and decrease in the east. There is a likelihood of increased drought frequency due to higher temperatures, increased evaporation and the possibility of more frequent El Niño (ENSO) events. Eastern New Zealand will be particularly vulnerable to the latter. The consequences of such climate change for New Zealand wool production are likely to be mixed. Gains could be experienced in the west due to the positive effects of increased rainfall and CO_2 fertilisation (where soil nutrients levels are non-limiting) on growth of pasture and fodder crops, as well as the potential reduction in cold-stress induced livestock mortality as minimum temperatures rise. In contrast, there could be negative effects on wool production in eastern New Zealand with reductions in rainfall and increased drought potentially offsetting any gains in pasture and fodder crop growth from elevated CO_2, as well as affecting water availability for livestock. As with Australia, pests, woody weeds and diseases could negatively affect both wool production and quality. However, given the generally cooler climates in New Zealand, heat stress is less likely to be an issue. Overall, the potential effect of climate change on New Zealand wool production is unlikely to greatly impact on the Australian market, with possible loss in production in eastern New Zealand balanced by gains in the western New Zealand. However, there would be value in further exploring the potential impacts of climate change under different scenarios of market influence and structural change.

Wool production in China occurs in both the arid/semi-arid and temperate regions (Longworth and Brown, 1995; Adger et al., 2001). In arid/semi-arid China a decrease in summer rainfall (by up to 2.1%) coupled with the potential increase in drought frequency could lead to water stress and the possible expansion of deserts (Adger et al., 2001). This in turn might accelerate pasture deterioration and land degradation in the pastoral region – two issues that are already seriously affecting both the quantity and quality of wool production in China (Longworth and Brown, 1995). Low soil nutrient levels in this region combined with the projected decreases in summer rainfall are likely to offset benefits of rising CO_2 concentrations to pasture and fodder crop growth. A greater frequency of drought, pasture deterioration, higher summer temperatures and an increased incidence of pests and diseases under warmer climates are 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; Patterson et al., 1999; Adger et al., 2001). This stress may be alleviated to some degree by higher winter temperatures and lengthening of warm seasons, both of which have the potential to improve wool fibre quality.

In temperate China the combined effects under future climate change scenarios of higher rainfall, CO_2 fertilisation and a longer frost-free period are likely to enhance the growth of pasture and fodder crops (Rosenzweig and Hillel, 1998; Adger et al., 2001) and in turn wool production. The fibre quality of wool grown in this region is also likely to be improved by warmer winters, although heat stress from hotter summers may have some negative effects. The potential benefits to wool production in this region could be moderated to some degree by an increased frequency of drought, the spread of pests and diseases, and the spread of woody weeds. The latter might raise the potential for increased vegetable fault – already an issue in Chinese wool production (Longworth and Brown, 1995).

Overall, climate change scenarios indicate that China's production of wool might benefit from climate change, particularly in regard to fine wool produced from the temperate wool producing region. This could lead to a reduction in the amount of wool that China purchases from Australia, which in turn could have negative ramifications for prices on international markets.

4.7. Scenario integration of climate change and other issues affecting the Australian wool industry

The actual impact of the issues reviewed above on the wool industry as a whole over the next 25 years is likely to depend in part on what changes the wool industry is experiencing as a result of other drivers of change. To explore the interaction between the issues reviewed above with future climate changes we carried out a brief qualitative scenario analysis.

4.7.1. Methodology

Scenario planning is a method for taking into account the impacts of various uncertain factors that are thought to be significant but whose probabilities are essentially unquantifiable. It was developed in the business sector, in particularly by Royal Dutch Shell (Schwartz, 1996), but is increasingly being used in environmental and natural resource management. Examples include, characterising how the global economy may develop in order to assess future climate change, assessing continental land use change and global water resources, and informing biodiversity management (Nakicenovic et al., 2000; Almaco, 2001; Peterson et al., 2003). The core of the technique is to develop a small number of plausible stories about the future of the system of interest based on the different actions or outcomes of various uncertain drivers. The purpose is not to predict or even bracket the range of possible outcomes for the systems, rather it is to explicitly sample some of the variation in the possible future to aid planning. Descriptions of the scenarios may be partially quantitative, but the core differences between them are essentially subjective. The scenarios can then be used as basis for examining variation in the possible outcomes of given factors of interest, for example business strategy, natural resource management or the impacts of specific drivers of change. In this sense, the scenarios are somewhat analogous to the blocks in a randomised block experimental design, and the factors of interest are analogous to the experimentally varied factors (Dunlop et al., 2002).

In this study we explored the consequences of a single set of climate change related impacts on two baseline scenarios (Table 2) that were designed to represent the possible trajectories (derived from non-climate-change drivers) for the Australian wool industry over the next 25 years. The baseline scenarios were developed by qualitatively assessing a range of possible drivers of change in the Australian wool industry (see Walcott (2001) and Dunlop et al. (2002) for discussion of various drivers of change for Australian agriculture and additional projections and scenarios). The

Table 2
Baseline scenarios used in the analysis of the potential impact of the interaction between climate change and other issues affecting the Australian wool industry

Issue	Baseline scenario 1	Baseline scenario 2
Relative profitable of wool	Wool remains less profitable than cropping in the wheat-sheep zone	Wool (and lamb) prices continue their recent increases, raising the relative profitability of sheep production
Land use change drivers	The area used for sheep is largely determined by changes in productivity of cropping and other land uses	Productivity increases in sheep production as important as productivity of other land uses
Crop-sheep balance in wheat-sheep belt	There is increased cropping intensity and water use efficiency across the wheat-sheep belt	Cropping intensification reaches a limit, grazing remains an important part of most mixed crop production systems
Crop-sheep balance in high rainfall areas	There is a steady expansion of cropping into high rainfall areas and expansion of agroforestry - both displacing sheep grazing	The expansion of cropping into higher rainfall areas is very limited. Similarly, agroforestry remains small-scale
Crop-sheep balance at the dryer margins	There is a reduction in cropping at drier margins of the wheat-sheep belt which sees an expansion of sheep grazing	There is a reduction in cropping at drier margins of the wheat-sheep belt which sees an expansion of sheep grazing

scenarios were not intended to be predictions for the wool industry. Rather, they represent two different possible outcomes from a range of plausible futures.

In the first baseline scenario the wool production remains secondary to cropping, and particularly in the more productive and wetter areas wool production is constrained by the expansion and intensification of cropping. In the second baseline scenario the sheep industry experiences an upturn and holds its place as a significant component of the agriculture systems throughout the wheat-sheep and high rainfall zones. For each of these baseline scenarios we considered the possible consequences of a range of climate change related impacts that were drawn from the discussion Sections 4.1–4.5 and are summarised in Table 3. The consequences of these impacts were assessed subjectively by the research team.

4.7.2. Results and conclusion

The two impact scenarios (Table 3) result from the interaction of climate related impacts and other drivers of the industry (as captured by the baseline scenarios, Table 2). They illustrate the importance of the interaction between water availability, CO_2 effects on pasture growth, market forces, and water relations, particularly in regard to the interplay between cropping and grazing, under future climate change.

The impact of climate change was more negative on the already depressed wool industry represented by scenario 1. However, overall the interaction of climate change and other industry drivers did not produce a clear overriding positive or neg-

Table 3
Two potential future scenarios for the Australian wool industry derived from applying a set of climate impacts to the baseline scenarios outlined in Table 2

Issue	Climate impact	Impact on scenario 1	Impact on scenario 2
Crop vs pasture	a general decrease in suitability of drier areas for cropping and improved conditions for cropping on wetter margins of the wheat belt (although there is much regional variation in these trends)	Shift of cropping into high rainfall zone is accelerated by climate change, with considerable areas of pasture lost and marked reductions in fine wool production	Some expansion of cropping in higher rainfall areas facilitated by climate change Reductions in area under crop and expansion of pasture on drier margins are much more significant
Re-vegetation	Increased demand to reduce the impacts of climate change on biodiversity through habitat establishment	Re-vegetation for biodiversity conservation under climate change is largely at expense of pasture	Re-vegetation for greenhouse gas mitigation and biodiversity in high rainfall and wheat-sheep zones provides additional shade
Pasture production and animal health	Increased temperatures and CO_2 concentration Increased impact of weeds Reduced sever frosts Increased livestock water demand	Pasture condition and animal health negatively affected as producers lag in their response to new climatic conditions, especially those focussing on cropping Ready availability of feed grain and shade from agro-forestry plantings alleviates some pressure in high rainfall zone	Retained focus on sheep production in farming systems sees faster adaptation to climate change in management of animal health and pasture
Water availability	Decreased water availability and increased livestock water demand	Expanded cropping and increased crop water use efficiency (less runoff and seepage) combine with climate change leading to substantial pressures on water for stock and reduced stream flows	Some reductions in water for stock
Dry years	Increased frequency	Fewer sheep and ready supplies of feed-grain make more frequent dry years easier to manage in high rainfall zone	Managing more frequent dry years is increasingly challenging
Greenhouse gas emissions	Increased community awareness of climate change (and its human causes) and demand to reduce its rate and magnitude through sequestration and emission reductions	Sequestration of carbon through agro-forestry and some woody re-growth in drier areas retired from cropping helps reduce agriculture's net greenhouse gas emissions. Demand for reduced greenhouse gas emissions from sheep is largely met by reduced sheep numbers in most of the wheat-sheep zone and the higher rainfall zone	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 to timber. The demand for reduced emissions from sheep places added pressure on wool production

ative impact of climate change on the wool industry in either scenario. Thus, we draw the tentative conclusion from the impact scenarios that, although it will be affected by climate change, as a whole the wool industry is likely to be relatively robust. This arises partly because of the geographic and production system diversity of wool growing in Australia.

Although the scenarios were not detailed, they do illustrate how the impacts of climate change are likely to vary among regions and have different impacts on fine and coarse wool production. It is also clear from the scenarios that the overall impact of climate change may vary considerably depending on the specific impacts of the non-climate drivers of change, and there is potential for some synergies in terms of management. For example, re-vegetation could provide carbon sequestration, biodiversity conservation and shade for stock to combat the effects of heat stress. Early adaptation, for example through efforts to produce low emission grazing systems, more sustainable management especially in the rangelands, and improved management of the effects of climate variation, could significantly reduce the downsides of climate change impacts.

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