CSIRO PUBLISHING

Crop & Pasture Science, 2012, **63**, 191–202
http://dx.doi.org/10.1071/CP11169

Livestock production in a changing climate: adaptation and mitigation research in Australia

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Abstract. Climate change presents a range of challenges for animal agriculture in Australia. Livestock production will be affected by changes in temperature and water availability through impacts on pasture and forage crop quantity and quality, feed-grain production and price, and disease and pest distributions. This paper provides an overview of these impacts and the broader effects on landscape functionality, with a focus on recent research on effects of increasing temperature, changing rainfall patterns, and increased climate variability on animal health, growth, and reproduction, including through heat stress, and potential adaptation strategies. The rate of adoption of adaptation strategies by livestock producers will depend on perceptions of the uncertainty in projected climate and regional-scale impacts and associated risk. However, management changes adopted by farmers in parts of Australia during recent extended drought and associated heatwaves, trends consistent with long-term predicted climate patterns, provide some insights into the capacity for practical adaptation strategies.

Animal production systems will also be significantly affected by climate change policy and national targets to address greenhouse gas emissions, since livestock are estimated to contribute ~10% of Australia's total emissions and 8–11% of global emissions, with additional farm emissions associated with activities such as feed production. More than two-thirds of emissions are attributed to ruminant animals. This paper discusses the challenges and opportunities facing livestock industries in Australia in adapting to and mitigating climate change. It examines the research needed to better define practical options to reduce the emissions intensity of livestock products, enhance adaptation opportunities, and support the continued contribution of animal agriculture to Australia's economy, environment, and regional communities.

Received 6 July 2011, accepted 14 March 2012, published online 28 May 2012

Introduction

Livestock are a global resource for both developing and industrialised societies. They provide multiple benefits that include food, clothing, fuel, nutrient cycling for soils, draught, income and employment, and a means of future food and income insurance against climate and weather-associated risks. Livestock production systems are also significant for the fact that they occupy almost one-third of the global ice-free terrestrial land surface (Steinfeld *et al*. 2006). In many regions, they represent the only viable system of food production and enable communities to inhabit, and prosper in, arid and semi-arid regions. However, animal agriculture also represents a major use of natural resources and, in part due to the fragile landscapes with highly variable climate that livestock often occupy, has been associated with extensive land degradation. Recently, the negative impacts of human-induced global warming on livestock production systems (Tubiello *et al*. 2007) and the contribution of livestock to climate change (Steinfeld *et al*. 2006) have been highlighted. Animal agriculture has been attributed with 8–11% of global anthropogenic greenhouse gas emissions (O'Mara 2011).

The United Nations predicts that the global population could grow to over 9 billion by the middle of the 21st Century, with ~70% of people living in urban areas, compared with 50% currently (UN 2008). Food demand is projected to grow by 70% by 2050 (FAO 2006). The majority of population growth will occur in developing countries, and food security—production, access, and affordability—will become an even greater challenge than it is today. A shift in wealth in developing countries is predicted to increase the capacity of a new 'middle class' with the means and desire to move from a predominantly grain-based diet towards one with more animal protein (Rae and Nayga 2010). Additionally, people—

particularly those with higher incomes—will increasingly want to understand more about the origins, quality, and environmental impact of their food products.

The future for livestock production in Australia will require adaptation to a complex suite of impacts linked to climate change: higher temperatures; changes in rainfall amounts, intensity, and patterns; requirement for greenhouse gas mitigation; potential competition for rural land resources for production of human food, animal feed, biofuels, and carbon sequestration; increasing input costs due to water pricing and higher energy costs; and expectations that sustainable production and environmental stewardship be not only practised but demonstrated. Some climate change response options will provide 'win–win' benefits, with adaptation strategies also contributing to emissions reduction. However, in other cases there will be a trade-off and difficult choices such as sacrificing some profitability to meet mitigation policy requirements. In Australia, livestock production is the primary land use on 47% of the continental land mass (ABS 2010) (Fig. 1).

This paper examines the major climate change challenges and opportunities, and the research and development needs, for animal agriculture in Australia, focusing on ruminant livestock. Ruminants are attributed with more than two-thirds of emissions from the agriculture sector and have fewer established technologies for mitigation than non-ruminant industries such as intensive pork and poultry industries, where the generation of renewable energy from methane is already a relatively mature technology.

The impacts of climate change policies will not be analysed in detail in this paper. If livestock producers are to meet growing demand and contribute to global food security, Sheales and Gunning-Trant (2009) note that Australia must face the productivity challenges caused by climate change by adopting innovative and successful practices that are supported through investment in targeted research and development and policy settings. Hence, mitigation policies need to recognise the unique challenge to decrease absolute emissions, largely through reduced emissions intensity, while meeting the growing global demand for food and fibre products.

Climate change impacts on livestock production

Climate change projections

Effects of climate change on livestock production systems in Australia will be superimposed on high natural variability in climate. Some impacts, especially rainfall, are difficult to predict, but it is highly likely that agriculture will face changes that include:

- Higher temperatures with averages projected to rise by 0.6–1.5°C by 2030 and 2.2–5°C by 2070 (CSIRO and BoM 2010);
- Changes in annual rainfall with projections for 2030 ranging from –10 to +5% across northern Australia and from –10% to no change in southern Australia, and projections for 2070 under a high emissions scenario of –30 to +20% in northern, central, and eastern Australia, and –30 to +5% annual rainfall across southern Australia (CSIRO and BoM 2007);
- Changes in the frequency, intensity, and duration of extreme weather events and climate-related variables such as soil moisture which will affect productivity, sustainability, and business planning for livestock enterprises, with likely economic, environmental, and stress consequences (Table 1);
- Intensified water security problems with the frequency and extent of droughts projected to increase over most of southern Australia (CSIRO and BoM 2007).

The predicted distribution of climate change over the continental land mass (Fig. 2b, c) shows that regions of ruminant livestock production (Figs 1, 2a) cover the full range of change. Under this moderate emissions scenario, there was a warming across the continent with greater warming inland (1–1.2°C) than in coastal regions (0.7–0.9°C) and generally a small decline in annual rainfall over much of inland and northern Australia, being more pronounced in the south-west and south-east.

Impacts of a changing climate

Climate change, and related variations in climatic conditions, could have a significant impact on the economic viability of livestock production systems in Australia. Rötter and Van de

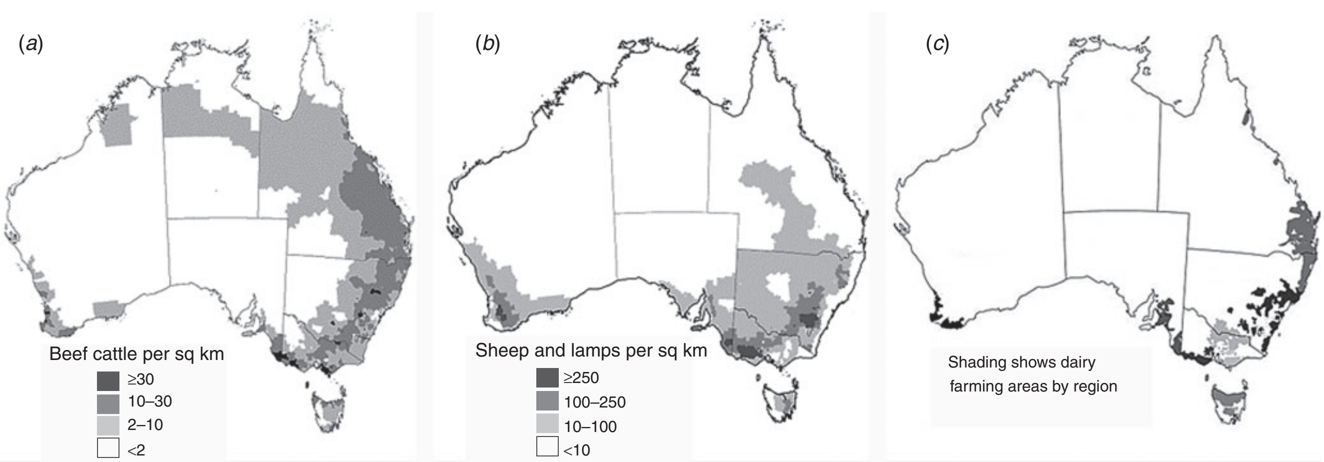

Fig. 1. Distribution of (a) beef cattle (25 million head), (b) sheep (73 million head), and (c) dairy cattle (2.6 million head) in Australia. Livestock numbers for 2009. Sources: a, b, Australian Bureau of Statistics; c, Dairy Australia (www.dairyaustralia.com.au).

Table 1. Examples of projected changes in climate variables of relevance to livestock production (CSIRO and BoM 2007)

Climate related variable	Projected change	Confidence in projection
No. of hot days and nights	Increase	Virtually certain
No. of cold nights	Decrease	Virtually certain
No. of warm spells and heat waves	Increase	Very likely
No. of heavy precipitation events	Increase	Very likely
Extent of drought affected areas	Increase	Likely
Fire weather risk	Increase	Likely
Soil moisture	Decrease	Likely (southern Australia)

Geijn (1999) suggested that any shifts in climatic conditions could affect animal agriculture in four primary ways: (*i*) feed-grain production, availability, and price; (*ii*) pasture and forage crop production and quality; (*iii*) animal health, growth, and reproduction; and (*iv*) disease and pest distribution.

The effects of projected increases in temperature, changes to rainfall patterns, and elevated atmospheric carbon dioxide (CO_2) (CSIRO and BoM 2010) on productivity of grazing systems will vary regionally and will depend on the combination of changes (Harle *et al.* 2007; Howden *et al.* 2008; McKeon *et al.* 2009). Shorter term changes due to extremes in weather, such as extended drought, heat waves, and flooding (Table 1) will further add to these challenges (Barlow *et al.* 2010). While uncertainty in some future climate projections is high, there is little doubt that the future climate will be warmer. Hence, the effects of higher temperature on livestock and their forage base is the most certain impact. Effects of rainfall would be more speculative.

There is a need for greater understanding of how the biology of animals will be affected by the direct effects of climate change and the indirect effects on disease/parasite exposure and feed quality through effects on plant and soil systems. The lack of experimentation and simulation of livestock physiology and adaptation to climate change makes it difficult to predict impacts or develop adaptation strategies (Hoffmann 2010).

The predicted changes in climate and weather are likely to result in more variable pasture productivity and quality, increased livestock heat stress, greater pest and weed effects, more frequent and longer droughts, more intense rainfall events, and greater risks of soil erosion (Stokes *et al.* 2010). Climate change may also impact on grazing systems by altering species composition in mixed swards. For example, warming will favour tropical (C4) species over temperate (C3) species, with associated changes in pasture quality (Howden *et al.* 2008). Cullen *et al.* (2009) modelled pasture production for a range of future climate change scenarios and reported a trend towards C4 grass dominance in subtropical and subhumid climates, where modelled climate projections indicated warming of up to 4.4°C with little change in annual rainfall.

Increased atmospheric CO_2 concentration has mixed effects on plant growth and quality, which is further complicated by differences in metabolic pathways between C3 and C4 plants (Stokes *et al.* 2010). Evidence suggests that increasing CO_2 levels *per se* increase productivity, but reduce plant quality through reduced protein concentration and digestibility, particularly in C3 plants. C4 plants are often cited as being less affected by quality change (Stokes *et al.* 2010). Furthermore, increased CO_2 concentration will result in increased water use efficiency (Eamus 1991), albeit in a water-impoverished landscape.

Climate change could also increase productivity and reduce weather-related challenges in many regions. In Mediterranean, temperate, and cool temperate climates, Cullen *et al.* (2009) predicted increased pasture growth rates in winter and early spring, counteracted by a predicted shorter spring growing season. In a cool temperate environment in Tasmania, annual production was predicted to increase under plausible future climate scenarios modelled through to 2070. In subtropical regions, lower rainfall and increasing intensities of drought in savannah areas may be partially offset by benefits of higher CO_2 levels and associated increased growing season (Howden *et al.* 2008; McKeon *et al.* 2009). In northern areas, such as the Kimberley, increased rainfall could result in greater pastoral productivity. Wetter areas traditionally used for grazing may shift to cropping if rainfall decreases, a trend already noted in south-western Victoria (Barlow *et al.* 2010).

Adaptation to climate change

The drought over much of Australia throughout the 10 years to 2009, several heat waves, and flooding in many areas during 2010 and 2011 have been consistent with predicted long-term climate patterns, providing some insights into potential

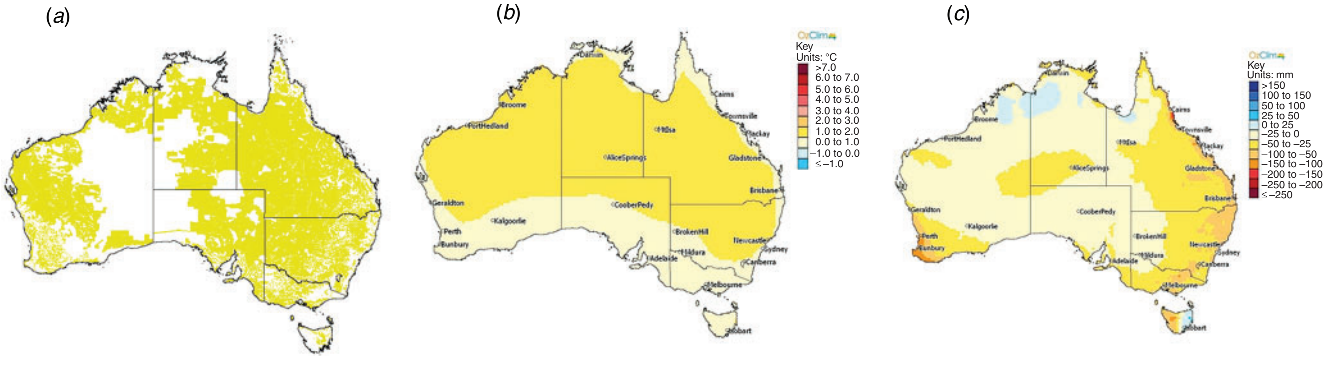

Fig. 2. Distribution of (*a*) 'grazing land' in Australia and projected change in (*b*) mean surface temperature (°C) and (*c*) total rainfall (mm) for the year 2030 relative to a base period of 1975–2004 using the CSIRO EACHAM5/MPI-OM model (www.csiro.au/ozclim).

adaptation strategies graziers may adopt. In northern Victoria, the dairy industry has seen dramatic changes to their production systems over the past 12 years in response to reduced water allocations. Before the drought, most farmers in this region used flood irrigation on perennial pastures throughout the dry summer months. However, over a period of 3–5 years, these systems changed to supplementary irrigation of more water-use-efficient forages (e.g. maize, annual ryegrass, lucerne) during the less evaporative months of the year. This has dramatically increased water use efficiency, potentially simultaneously increasing total annual production (Lawson *et al.* 2009).

Heat stress

As a result of thermal challenges associated with climate variability and change, normal behavioural, immunological, and physiological functions of animals are all potentially impacted (Nienaber and Hahn 2007). In addition, when animals are exposed to thermal stress, metabolic and digestive functions are often compromised due to altered or impaired feeding activity (Mader 2003). These effects could potentially result in changes in the types of animals and genotypes that are used, changes in facilities and housing utilised for care and management of livestock, and eventually a potential redistribution of livestock and livestock species in a region (Gaughan *et al*. 1999, 2009).

Livestock will normally maintain their body temperature within a fairly narrow range (±0.5°C) over the course of a day. Exposure to high heat load will induce a heat stress response as the animal attempts to maintain homeostasis. When environmental conditions change, an animal's ability to cope with (or adapt to) the new conditions is determined by its ability to maintain performance and oxidative metabolism (Pörtner and Knust 2007). The stress response is influenced by several factors including: species, breed, previous exposure, health status, level of performance, body condition, mental state, and age. Insufficient acclimatisation or adaptation would determine what an animal experiences as stressful. Subsequent acclimatisation or adaptation may alleviate the stress response (Kassahn *et al*. 2009). Animal response to stress usually results in a loss of performance (e.g. growth or reproduction) before cellular and molecular stress responses are activated (Kassahn *et al*. 2009), suggesting that the use of biological stress markers as an aid in selection may be limited. Under extreme conditions, there may be an increase in mortality rates. All of these changes lead to economic loss (St-Pierre *et al*. 2003).

Effects of high heat load can be minimised using three basic approaches (Renaudeau *et al*. 2010): (*i*) adjusting the environment, (*ii*) nutritional manipulation, and (*iii*) selection for thermal tolerance. A fourth option may be to change the species, e.g. goats rather than cattle. The two main strategies to improve heat exchange between an animal and its environment are: (*i*) ameliorate thermal heat load, e.g. by the use of shade, misters, foggers, or pad cooling; and (*ii*) improve the ability of the animal to dissipate body heat by increasing sensible heat or increasing evaporative heat loss, e.g. using sprinklers to wet animals. However, sensible and evaporative heat losses are interdependent, so using one without the other may not be effective.

Water restriction will further increase the negative aspects of high heat load by decreasing evaporative heat loss, leading to further reductions in feed intake, so access to cool clean drinking water to meet potential peak demands is paramount. Water intake may increase markedly during periods of high heat load, e.g. in a feedlot study mean water intake increased from 32 to 82 L per steer per day as heat load increased (Gaughan *et al.* 2010). Nutritional strategies used include changes to feeding frequency and time of feeding, and changes in ingredients, e.g. addition of dietary fat to increase energy density, or additional roughage added to cattle diets to reduce heat increment. These sorts of adjustments are not easy to do in an extensive grazing system.

Breeding goals may have to be adjusted to account for higher temperatures, lower quality diets, and greater disease parasite challenge. Species and breeds that are well adapted to such conditions may become more widely used (Hoffmann 2010). Genetic variability for heat tolerance within a species occurs within and between breeds. Functional genomic research is being undertaken to identify the genes expressed during heat stress in order to gain a better understanding of heat resistance mechanisms. If successful, this may allow for improved thermal tolerance via gene manipulation (Renaudeau *et al*. 2010).

Disease

Increasing temperature may also increase exposure and susceptibility of animals to parasites and disease (Marcogliese 2001; Sutherst 2001), especially vector-borne diseases (Tabachnick 2010). However, little effort has been dedicated to understanding the potential impact of climate change on parasite populations and subsequent effects on animal production (Marcogliese 2001; Tabachnick 2010).

Many important animal diseases are affected directly or indirectly by weather and climate. These links may be *spatial* (with climate affecting distribution) or *temporal* (with weather affecting the timing of an outbreak), or may relate to the *intensity* of an outbreak (Baylis and Githeko 2006). Understanding the complex interactions between pathogens, vectors, host, and climate is difficult due to the multivariate nature of climate change and the non-linear thresholds in both disease and climate processes (Marcogliese 2001; Harvell *et al.* 2002; Patz *et al*. 2008; Mills *et al.* 2010). Therefore, the ability to predict the effect of climate change on disease is difficult to achieve (Mills *et al.* 2010; Tabachnick 2010).

Vectors and pathogens may move in and out of an area due to changing climatic conditions. For example, buffalo fly (*Haematobia irritans exigua*), a tropical biting fly, has appeared in Victoria (south-eastern Australia) during hot wet summers. During mild winters, these flies may overwinter as far south as the Hastings River in New South Wales (31.426S, 152.916E). The spread of tropical parasites south is likely to continue, whereas there could be contractions in some temperate species (e.g. lice) (Sutherst 2001). Climate modelling suggests that cattle tick (*Rhipicephalus microplus*) can spread well south (Sutherst 2001), but spread in Australia is limited by the regulated control of cattle movements.

In summary, the ability of livestock producers to adapt to the long-term impacts of climate change is influenced by the uncertainty of projected changes and their impacts and the time frames for normal farm management planning. Investment in research to better understand the direct and indirect effects of climate change on animal production systems is needed to develop strategies for longer term adaptation. However, adaptive responses to the extremes in climate already being experienced by Australian livestock producers, such as the management adjustments of dairy producers described above during the recent extended drought period, provide confidence in their capacity to implement adaptation strategies to minimise negative impacts of future climate change on productivity and sustainability, at least in the near-term.

Mitigation options for livestock

Australian agriculture contributes around 15% of national greenhouse gas emissions, with the livestock industries contributing around 10% of this total. The agriculture sector is the dominant national source of both methane and nitrous oxide (N_2O), accounting for 58.0% and 75.5%, respectively, of the net national emissions for these two gases (DCCEE 2010*a*). Emissions from agriculture have been approximately stable since 1990, with 2008 emissions being 0.7% higher, while livestock emissions have fallen by 10.7% over the same period, due largely to declining sheep numbers.

Brief introduction to policy settings in Australia

In November 2009, the Federal government announced a decision to exclude agricultural emissions from any future emissions trading scheme. However, there is an expectation that agriculture will contribute to reducing Australia's greenhouse gas emissions, given that the sector is the second highest contributor to total national emissions after the energy sector (DCCEE 2010*a*). In 2011, the Carbon Farming Initiative (CFI), which provides an offset mechanism for agriculture to contribute to mitigation under exclusion from an emissions trading scheme or price on carbon, was passed into law (DCCEE 2010*b*). All offsets rewarded under the CFI will have to comply with a mechanism approved by the Domestic Offset Integrity Committee to ensure that they meet the appropriate standards of integrity. The CFI includes recognition of Kyoto offsets credits, i.e. sequestration in new reforestation and afforestation projects and real reductions in emissions of methane and N_2O, and also incorporates non-Kyoto credits, such as increased sequestration of soil carbon, managed forests, and non-forest vegetation, thus incorporating the domestic offsets eligible under the National Carbon Offset Standard (NCOS).

The Australian CFI provides an incentive to develop several technologies and management strategies reviewed in this paper into offset methods. The purpose of this would be to provide financial incentives to farmers for the adoption of these technologies through the sale of offset credits. Before an offset method can be developed the underpinning science needs to be well established in the peer-reviewed literature, and/or the method needs to provide sufficient evidence that a real reduction in methane and/or N_2O will result (e.g. reducing animal numbers). These offset methods also need to consider the potential for leakage if, for example, reducing the stocking rate results in other producers expanding their animal numbers to fill a gap created in the market.

Of the technologies and management strategies currently being considered, this review focuses on those sufficiently supported by the underpinning science. For reducing enteric methane, adding oil supplements to ruminant cattle diets (particularly dairy cattle) is supported by several recent reviews (Eckard *et al*. 2010; Martin *et al*. 2010; Grainger and Beauchemin 2011; Moate *et al*. 2011). Likewise, any management system that results in a net reduction of animal numbers should be eligible for inclusion as an offset method for reducing both methane and N_2O (Eckard *et al*. 2010). Ideally, reduced stocking rate should result in increased individual animal performance and not be counteracted by increased stocking rates elsewhere in the system (leakage). For example, reducing the stocking rate across an over-grazed region could improve both forage quality and individual animal performance, resulting in no net change in growth or reproductive productivity.

Offset methods for reducing N_2O could include reductions in annual N fertiliser rates, spraying a nitrification inhibitor on intensive pastures, coating fertilisers with inhibitors, and balancing the energy-to-protein ratios in ruminant diets (de Klein and Eckard 2008). As the annual N fertiliser rate is the key input into national inventory Tier 1 and Tier 2 methods (DCCEE 2010*a*), offset methods that result in net reductions in annual fertiliser rate would be reasonably simple to implement. Likewise, nitrification inhibitors, used as a coating on fertiliser or as a spray, have been well documented for temperate latitudes in Australia (Kelly *et al*. 2008) and New Zealand (Di *et al*. 2009, 2010; Qiu *et al*. 2010; de Klein *et al*. 2011).

Enteric methane

Farm management and early-stage test results of technologies being developed to reduce emissions of enteric methane have been extensively evaluated (McAllister and Newbold 2008; Buddle *et al.* 2011; Eckard *et al.* 2010). In the context of human food security, the most relevant measure is 'emissions intensity' (emissions/unit product), with the objective being to produce food with the lowest greenhouse gas footprint achievable while giving consideration to other environmental impacts. The objective of reducing emissions intensity enables farmers to change farm practice in ways that are consistent with production and financial efficiency of their enterprise and potentially earn additional income through sale of carbon credits registered under domestic policy arrangements in the CFI. For livestock producers, these operational changes seek to increase production per head per year and can be achieved by means described in Table 2.

Reduction in total and emissions intensity plus increased animal performance can be achieved by feeding supplements that contain levels of lipid to increase dietary concentration of lipids to 6–8% (Grainger *et al.* 2008). Lipids and potentially other supplements that may reduce emissions (e.g. tannins, saponins) can be applied year-round in feedlots and dairy farms where scope exists to modify animal diets on a daily basis.

Manipulating microbial populations in the rumen, through chemical means by introducing competitive or predatory microbes, or through vaccination approaches, can reduce methane production. Many of these techniques are in the early stages of research in terms of a practical and cost-effective method

Table 2. Practical changes with productivity and greenhouse gas mitigation benefits

Option	Enterprise	Reference
Feed	Change from native to improved pasture	Alcock and Hegarty (2006)
	Increased use of dietary oils	Grainger *et al.* (2008)
	Increased feeding of leucaena	Jones *et al.* (2009)
Breeding	Change breed to tropically adapted	Bentley *et al.* (2008)
	Change breed to tropically adapted	Beukes *et al.* (2009)
	Use more fecund genotype	Cruickshank *et al.* (2009)
	Faster growing genotypes	Alcock and Hegarty (2006)
Management	Reduce age at first breeding	Cruickshank *et al.* (2009)
	Extended lactation	Eckard *et al.* (2010)
	Increased use of feedlot finishing	Hunter and Neithe (2009)
	Reducing age to slaughter	Rolfe (2010)

of abatement (Henry and Eckard 2009). Bacteria introduced to detoxify mimosine in cattle grazing leaucaena have been shown to maintain activity in the herd over 25 years (Jones *et al.* 2009), and if such persistence and efficacy can be achieved by exogenous reductive acetogens or methane-oxidising organisms on introduction to the rumen, their use as microbial additives may provide a cost-effective mitigation strategy. Ecological change by eliminating organisms from the rumen rather than introducing new organisms can also have long-term impact, with some studies showing that sheep rendered free of protozoa may remain free for 3 years (Bird and Leng 1985). However, defaunation does not always persist or lead to reduced enteric emissions (Bird *et al.* 2008). The changes in animal productivity associated with these techniques or interventions such as vaccination against methanogens (Wedlock *et al.* 2010) require further research before consideration as practical mitigation options.

The extensive cattle industry

About half of the Australian cattle industry is based on extensive grazing systems, much of it in the tropical and subtropical regions of the country (ABARE 2006). These systems are characterised by having relatively high emissions intensity, in the range 20–30 kg CO_2 equivalents (CO_2-e)/kg saleable beef (Charmley *et al.* 2008; Rolfe 2010), and unique constraints when it comes to mitigation options. Differences in assumptions and methodology between different studies make comparisons difficult, but Peters *et al.* (2010) estimated two southern Australian beef production systems as having 12–18 kg CO_2-e/kg hot standard carcass weight (HSCW) while international studies have produced values of 6–26 kg CO_2-e/kg HSCW (Peters *et al.* 2010). Routine interventions and feed supplements are difficult or impossible to administer in extensive grazing systems. This severely restricts the use of anti-methanogenic feedstuffs (e.g. fats and oils) and feed additives (e.g. monensin). Possibilities exist for administering anti-methanogenic compounds in the water supply, in protein/energy/mineral feed blocks and licks, and via drought-fed supplements, but all these options are at the experimental or demonstration stages of development.

Selective breeding for increased feed efficiency and/or reduced methane emissions appears to be one option eminently suited to northern Australia (Alford *et al.* 2006). The benefit is inherent to the selected animal and is passed on from one generation to the next. As reduced methane emissions should be associated with increased feed efficiency, there would be economic advantage to selective breeding for high performance even if there was no financial incentive to reduce methane emissions. While the cost of a breeding program is high, the long-term benefits should be cost-effective, particularly if there is potential to earn income through a carbon market.

For the extensive cattle herd, major reductions in methane emissions intensity can be achieved by management options that increase the productivity of the breeder and, to a lesser extent, the productivity of the growing/finishing animal (Charmley *et al.* 2008; Beauchemin *et al.* 2011). The reproductive efficiency of cattle is low compared with other domesticated species to begin with. However, in northern Australia this is further exacerbated by poor conception and weaning rates compared with cattle in the temperate regions of southern Australia. Bortolussi *et al.* (2005) surveyed segments of the northern industry in the 1990s and found weaning rates varied between 50 and 80%. When this is coupled with low weaning weights of <0.3 of the maternal weight, it is clear that there is major scope for improvement in both weaning rate and weight. Reducing the days to slaughter can also have a marked effect on emissions intensity (Rolfe 2010), particularly when considering grazing systems that typically finish cattle at $\geq$3 years of age. Finishing cattle in a feedlot or improving pasture quality to increase liveweight gain and reduce the age at turn-off can have a marked influence on emissions intensity. For example, Hunter and Neithe (2009) demonstrated that, depending on the productivity of the pasture-based system, finishing in the feedlot could reduce emissions intensity by 25–50%. This reduction was achieved simply by reducing the age at slaughter. In some regions of northern Australia, phosphorus supplementation can mean significant increases in productivity, leading to fewer cows required for the same number of progeny and a faster rate of turnoff (Winter *et al.* 1990). This would reduce emissions intensity and, if cow numbers were reduced, would lead to net reductions in emissions with the same or improved production.

Reducing emissions intensity per animal through improved efficiency resulting from management change does present a dilemma. Raising cattle more efficiently can enable a property manager to increase stocking rate in response to economic imperatives (Rolfe 2010). Thus, although emissions intensity will decline, emissions per hectare will increase. On a global scale this may be positive as the proportion of low emissions beef in the global supply increases. Nationally, Australia's emissions from beef production will increase because more beef is being produced. A possible win–win scenario exists if selective reductions in stocking rate in over-grazed regions could lead to sustained production levels (same kg of beef per hectare but from fewer animals) through improved land condition and individual animal performance (Burrows *et al*. 2010). Alternatively, if carbon sequestration (e.g. from woody regrowth occurring in grazed woodlands previously cleared to increase grass production) could also act as an alternative revenue stream, overall profitability could be sustained and carbon balance improved through optimising cattle and carbon production across the landscape (Bray and Willcocks 2009; Donaghy *et al*. 2010). However, it should be noted that increased carbon sequestration in woody biomass is finite and ceases once the woody vegetation reaches a new biomass plateau, usually within 20–30 years (Donaghy *et al*. 2010).

Removal of plant biomass through grazing reduces the incidence of fire in many bioregions. In turn, this can contribute to vegetation thickening (more woody perennials; Bray and Willcocks 2009). Fire in itself is a potent source of greenhouse gases (Russell-Smith *et al.* 2009). Obviously, the balance between vegetation, cattle, and fire is complex and dynamic. Thus, the balance between emissions and sequestration is not straightforward. Quantitative data are scarce in this area, but new modelling based on studies of savanna burning is providing better evidence (Liedloff and Smith (2010).

Nitrous oxide

Nitrous oxide is primarily lost from grazing systems as a result of cultivation, legumes, N fertilisers, and animal excreta. These emissions can be from direct (fertiliser, dung, urine) or indirect sources. Estimation of indirect N_2O emissions assumes that some of the ammonia volatilised and the nitrate leached becomes N_2O in subsequent off-site processes and thus contributes further to total N_2O emissions (de Klein and Eckard 2008). Direct N_2O is primarily formed through denitrification, a microbial conversion of nitrate to N_2O. This process is maximised in warm, anaerobic (wet) soil conditions with large amounts of nitrate and available carbon present. To a lesser extent, some N_2O can be produced when soil ammonium is converted to nitrate in a process called nitrification (de Klein and Eckard 2008). In northern Australia, fire is a significant source of non-CO_2 emissions, including both methane and N_2O (Williams *et al*. 2004). Although the majority of fires in northern Australia are in non-grazed tropical savannas, prescribed burning to control wildfires in both grazed and non-grazed savannas could reduce non-CO_2 emissions by 1.4 Mt/year (Andersen and Heckbert 2009).

In intensive livestock systems, mitigation options include a focus on improving the efficiency of N fertiliser use on pastures or for feed production and reducing N losses from urine. Ruminants excrete 75–95% of the N they ingest, with excess dietary N increasingly excreted in the urine, while dung N excretion remains relatively constant (Castillo *et al*. 2000; Eckard *et al.* 2007). Of the dietary N consumed by ruminants <30% is utilised for production with >60% being lost from the grazing system (Whitehead 1995). Strategies for reducing N_2O emissions should, therefore, also focus on improving the efficiency of N cycling through the soil–plant–animal system. Reducing the amount of N in the diet and the solubility of dietary N (Jones *et al*. 1995) are two approaches which will reduce N losses in the urine.

The rate, source, formulation, timing, and placement of N fertiliser applications are important management factors affecting the efficiency of pasture growth responses, and thus potential N_2O losses from intensive pasture systems. When conditions are suitable for denitrification, N_2O emissions increase exponentially with the rate of N applied in any single application (Mosier *et al*. 1983;Whitehead 1995; Eckard *et al*. 2006*a*). Nitrate-based N fertiliser has been shown to result in higher N_2O emissions than ammoniated-N sources, when applied to actively growing pasture (de Klein *et al*. 2001; Eckard *et al*. 2003). A recent study showed a potential 80% reduction in emissions of N_2O, with only a 4% loss in pasture growth from dairy farming systems, when managed with strategic inputs of N fertiliser using urea-N, relative to N applied after every grazing rotation (Eckard *et al*. 2006*b*).

Apart from directly reducing N inputs into grazing systems, and managing N fertiliser, nitrification inhibitors are currently the only well-published technology available for reducing the loss of N_2O from soils, both directly and indirectly through reduced leaching of nitrate (de Klein and Eckard 2008). Fertilisers coated with nitrification inhibitor have been shown to be effective in reducing nitrification, and N_2O emissions by up to ~80%, as reviewed by (de Klein *et al*. 2001). Applied as a spray, nitrification inhibitors can also be effective in reducing N_2O emissions from animal urine by 27–91%, with pasture yield increases of 0–36%, depending on the magnitude of N loss (Di *et al*. 2007; Kelly *et al*. 2008; Smith *et al*. 2008). However, many of these studies have been conducted under optimal conditions for N_2O production and over short periods, so the potential on-farm abatement is likely to be more conservative than the published data. More-recent research has shown that the nitrification inhibitor dicyandiamide (DCD) can be fed to a ruminant and be transferred to the urine, targeting the inhibitor where and when required, thus requiring a fraction of the product compared with spraying an entire paddock (Ledgard *et al*. 2007); this technology therefore has potential to be cost-effective in more extensive grazing systems where an offset income could exceed the cost of feeding the inhibitor. Nitrification inhibitors are also temperature-sensitive, as evidenced by lower efficacy reported on dairy pastures in northern Victoria; Kelly *et al*. (2008) reported a 47% reduction in N_2O from urine patches for ~50 days in mid-spring and 27% reduction in N_2O for ~25 days when applied in midsummer. Their use has historically been restricted, mainly due to cost, and this is likely to remain the case unless there is an added incentive for their adoption.

Soil management strategies to minimise N_2O loss include removing nutrient and soil limitations to pasture growth, reducing soil compaction and thus anaerobicity, minimising soil disturbance and consequent mineralisation of soil N, and managing soil water through drainage and irrigation (de Klein and Eckard 2008; de Klein *et al*. 2010).

In extensive grazing systems, N_2O emissions are largely sourced from urine excretion and, to a lesser extent, from faeces. These more extensive production system diets are generally low in protein and at low stocking rates, thus urine and faeces are both low in N content and more sparsely distributed. Emissions per hectare would, therefore, be far lower than intensive livestock systems, leaving few options for viable mitigation strategies. In extensive systems, mitigation options may include managing the energy-to-protein ratios in stock, through pasture species and seasonal supplementary feeding (de Klein and Eckard 2008).

Future N_2O abatement strategies are likely to include innovative N fertiliser formulations, feeding inhibitors to animals, targeted plant breeding to improve energy-to-protein ratios in line with animal requirements, and/or including tannins to bind excess dietary N; breeding animals with improved N use efficiency and reduced urinary N loss; and strategies for manipulating soil microbial populations to reduce N_2O formation (de Klein and Eckard 2008; de Klein *et al*. 2010).

Metrics for greenhouse gas emissions and mitigation

The potential misinterpretation arising from inconsistent approaches to assessing climate change impact has been highlighted by Pitesky *et al*. (2009), who noted that the 2006 FAO report (Steinfeld *et al*. 2006) incorrectly compared a Life Cycle Assessment (LCA) of emissions from livestock production with an Intergovernmental Panel for Climate Change (IPCC) sectoral calculation of the greenhouse gas emissions for transport. National greenhouse gas accounts are based on the IPCC approach of reporting emissions and removals by sector, while the Global Warming Potential impact category of an LCA (sometimes referred to as the 'carbon footprint' of a product) estimates all emissions and removals associated with the production, use, and disposal of the product regardless of source category. Hence, an LCA for beef production would include not only the greenhouse gases from enteric fermentation and manure management, but also emissions associated with feed production and milling, slaughter, and the refrigeration, retail, cooking, and waste of meat product and transport across the supply chain.

Livestock producers seeking to contribute to climate change mitigation across their whole farm systems are interested in management strategies such as on-farm tree planting (afforestation or reforestation), and increased efficiency in the use of fertilisers, vehicle fuels, and electricity. In addition to environmental sustainability, farm enterprise management requires that productivity and profitability not be compromised. Consumers may also be interested in the impact of food production on environmental factors other than carbon, such as water use, which may also be assessed in LCA studies. Robust metrics must meet these needs in a transparent way. Whole farm systems modelling can ensure that mitigation strategies do not result in unanticipated increases in emissions elsewhere within the farm system, while LCA is important to ensure that a mitigation option does not result in increases in emissions within the supply chain. These impact analyses and associated metrics are likely to be a factor in marketing and offset protocols in future, and to have a role in managing the risk of 'leakage' or perverse outcomes for other environmental values.

Livestock production appears set to increase to meet the demands of an expanding and increasingly affluent society. Increases in efficiency will most likely continue to lead to a decrease in greenhouse gas intensity of production, i.e. CO_2-e per unit product, but as long as growth and demand outstrip the capacity for mitigation, absolute emissions from livestock as reported under IPCC guidelines for the agricultural sector will increase. Emissions intensity is meaningful to a farmer because it links management practices to both emissions and efficiency of production. However, domestic and international policies will need to address both absolute emissions and the emissions intensity to address the threat of climate change and achieve global food security.

Climate change research, gaps, and priorities for livestock

Collaborative research networks

Globally, investment in climate change adaptation and mitigation research has increased to meet national commitments to greenhouse gas abatement targets and to improve resilience to the impacts of a changing climate. Agriculture, as the sector of the economy that will arguably be most directly affected by climate change and a sector able to significantly contribute to mitigation goals, has benefited from recent funding. For example, in Australia, several national collaborative climate change research programs that commenced in 2009 are making significant advances in knowledge and technologies for livestock mitigation and adaptation. In addition, there is increased collaboration between scientists in Australia and those in other countries with expertise in agricultural research, particularly New Zealand. Key structures for developing international collaborative linkages include the Global Research Alliance, the Livestock Emissions and Abatement Research Network (LEARN), and the international Greenhouse Gas and Animal Agriculture conferences.

Gaps and research priorities

Following is a brief outline of some key priorities for research, development, and extension to meet current and emerging needs for sustainable livestock production in a changing climate.

Capacity

To assist livestock producers to adopt adaptive practices that build resilience in a changing climate, and to support integration of carbon management into farm business so as to improve productivity and farming sustainability, there is an ongoing need to train extension officers and agricultural consultants in all aspects of climate science, adaptation, mitigation, and sequestration management. Appropriately linking research, notably mitigation for livestock production, to relevant current and emerging climate change policies will ensure accurate and consistent messages reach the farming community to promote opportunities for farmers and optimise their contribution to national net emissions reduction targets.

Adaptation

In Australia, adoption of management changes for longer term adaptation is currently limited by uncertainty in climate change science, uncertainty in the impacts of climate change, and limited information on the best response strategies for profitable farming enterprises. Research is needed to better understand the direct and indirect effects of climate change on animal production systems for development of regionally applicable, longer term adaptation strategies (e.g. Garnaut 2011). For livestock industries there is a specific and urgent need for greater understanding of how the biology (behavioural, immunological, physiological, and metabolic functions) of animals will be affected by the direct effects of climate change, and greater understanding of the indirect effects on disease/parasite exposure and feed quality through effects on plant and soil systems (Gaughan *et al*. 2009).

Our understanding of the impact of climate change on the feedbase is more advanced, and new models, such as mosaic agriculture, are emerging that will increase the resilience of livestock farming across Australia (Stokes *et al*. 2010). Whole farm systems modelling needs to shift from modelling climate change impacts for current plants, animals, and management practices, to evaluating adaptation options as identified by the researchers and agro-ecosystem managers who would develop and implement those options.

Mitigation

The key mitigation priority is for development of practical on-farm options to reduce emissions without negative impacts on productivity. This requires research on:

- Improved accounting for greenhouse gas emissions and sequestration in livestock production systems and capacity to quantify mitigation (Cowie *et al.* 2012);
- Cost-abatement curves for a range of mitigation strategies, aligned with the appropriate and current protocols for the generation of offsets, to inform the agricultural sector of cost-effective management options;
- Whole farm systems modelling (e.g. Eckard and Cullen 2011) and LCA to ensure that mitigation management does not result in unforseen increases in other emissions on-farm, or leakage along the supply chain;
- Understanding of the compatibility of proposed mitigation strategies with future climate and adaptation scenarios, e.g. (*1*) rising temperatures may affect waste management mitigation measures, and (*2*) potential for coordinating animal selection trial for simultaneous reduction in emissions intensity and enhanced heat tolerance.

In addition, knowledge gaps limit the capacity to develop practical on-farm strategies to manage major sources of emissions for livestock industries—enteric methane and excreta from ruminant animals. Some specific research priorities to address these gaps in current research programs in Australia are as follows.

Enteric methane

- *In vivo* measurements of enteric methane are required to establish the relationship between breeding for improved feed conversion efficiency and reduced methane emissions and quantifying heritability for low methanogenesis;
- Potential for rumen microbial manipulations which will most likely require sustained investment over many years due to the complexity and early stage of the research field;
- Continued research on dietary additives to explore new extracts, supplements, and forages, and combinations of these, and mechanisms for delivery of additives, integrated low-methane forage systems, supplements, and anti-methanogen agents, particularly for extensive grazing systems;
- Management strategies for improving conception and weaning rates for reducing enteric methane from extensive grazing systems;
- Integrated management strategies for improving productivity to reduce methane emissions intensity in extensive grazing systems such as improved pasture quality and N and P supplementation.

Nitrous oxide

Nitrous oxide research that is focussed on managing soils, tillage practices, and N fertiliser, with associated emission factors (Galbally *et al*. 2005), has delivered options for reducing emissions through managing the rate, source, timing, and placement of N fertiliser, but to date research on reducing urinary N and N_2O loss has been limited. Further research is required on innovative fertiliser and inhibitor formulations that are cost-effective and less temperature-dependent, but still provide the N to plants as required for production. Research is also required to decouple the strong dependence of plants on N inputs for production, e.g. through plant breeding.

Research is needed to improve quantification of indirect sources of N_2O resulting from nitrate leaching and ammonia volatilisation, and to develop mitigation options, including microbial options, and to improve inventory methods for accounting for indirect N_2O.

Conclusions

Livestock production will continue to make a significant contribution to food supply globally and in Australia. As a net exporter, Australia has a role in meeting global food security, and animal production will need to increase to meet increasing demand for animal protein and fibre. With further research this can be achieved with lower emissions per unit of product.

Australian research on climate adaptation is important to maintain profitability for livestock producers in this country, but it also has wider relevance and hence provides a potentially major contribution to regional developing countries. Australia's animal production occurs from cool temperate latitudes (43°S) through to the warm tropics (10°S), in regions that vary widely in seasonality of rainfall and which experience extreme variability in annual rainfall. This vast latitude range means that livestock production systems span a wide range in temperature extremes, allowing southern production systems to look further north for practical options to manage higher temperatures in a changing climate. For intensive livestock production systems, some adaptation strategies are already being implemented, e.g. to manage heat stress in dairy cattle, but ongoing adaptive adjustments will be needed to maintain sustainability and productivity due to increasing temperatures, changing rainfall patterns, and increasing climate variability.

In addition to continued improvement in climate adaptation, there is also a need to develop cost-effective strategies for managing emissions from animal agriculture. Success in contributing to addressing greenhouse gas emissions can be measured as a decrease in the emissions intensity of food products, even when absolute emissions rise with increasing production to feed an expanding global population. Strategies such as adding oil supplements to ruminant cattle diets (dairy cattle and beef cattle in feedlots) and improving reproductive efficiency are options available now to reduce enteric methane emissions while maintaining or improving productivity. Similarly, reducing N_2O can be achieved by reductions in annual N fertiliser rates, spraying a nitrification inhibitor on intensive pastures, feeding inhibitors to animals, coating fertilisers with inhibitors, and balancing the ratios of energy to protein in ruminant diets. However, further research into quantification and management through breeding, diet, and rumen manipulation is critical to realise the full potential of mitigation from livestock industries.

Therefore, further investment in climate change adaptation and mitigation is a priority for animal agriculture, in recognition of the limited options for mitigation currently available and of the broad environmental, economic, and social value of livestock production systems in regional Australia.

Acknowledgments

We thank Dr Brian Keating, Director CSIRO Sustainable Agriculture Flagship for his insights and expert review. We acknowledge the support of the Climate Change Research Strategy for Primary Industries, funding from the Department of Agriculture, Fisheries and Forestry Climate Change Research Program, Rural Research and Development Corporations, and several Australian research institutes for national research programs in mitigation and adaptation, including the Reducing Emissions from Livestock Research Program, Nitrous Oxide Research Program, Soil Carbon Research Program, and the Southern and Northern Livestock Adaptation Programs, which have contributed to the results reported in this paper.

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