Impacts of Climate Change on Livestock Systems: What We Know and What We Don't Know

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Abstract. Climate changes and the associated increases in atmospheric carbon dioxide concentration are just two of many possible future drivers of change in grassland systems and whilst there are significant uncertainties around these, they are probably more effectively characterised than many other drivers. The challenge for grasslands systems research is not so much trying to precisely predict future climate in the face of unresolvable uncertainty but rather to work with decision-makers to enhance their decisions for a range of possible climates, build their capacity to make sound risk-based and informed decisions and increase the array of options available for adaptation. There are many adaptations possible to address key climate impacts such as increased heat stress, altered pests and disease risk, vegetation change, increased risk of soil degradation and changes in forage quantity, quality and the variability of these. Many of these adaptations are extensions of existing best management practice. However, it is important to explore adaptations that are beyond incremental change to existing systems to be inclusive of more substantial systems change and even transformational changes. There is a need also to consider adaptations beyond the farm scale including in relation to value chains, institutional change and policy development. It is these areas in particular where there are likely to be increasing demands for research.

Keywords: Carbon dioxide, livestock systems, adaptation, institutional change, policy development.

Introduction

Livestock production systems globally face significant changes over the next decades. There are likely to be simultaneous increasing pressures for: more food for 2 billion more people expected by 2050, more grain for meat in more protein-rich diets, more cereals used to meet demand for more bio-fuel, more land used for greenhouse gas mitigation; and as these demands mount, available resources will increasingly be more strained, with less un-degraded land available for livestock production, less water for irrigation, and more expensive energy for fertilizer production. In addition there will likely be more pressure to reduce net greenhouse gas emissions and increasing desires in some countries to foster biodiverse landscapes and regions (Ingram *et al.* 2010). At the same time, there are likely to be substantial climate changes, which will alter food production, and its quality, variability and location, profitability and risk profiles, technology and management requirements, value chains and policy (Easterling *et al.* 2007). Under such scenarios, understanding climate change impacts on grassland livestock systems and how to adapt to these becomes a more immediate and critical concern.

Grassland-based livestock production systems occur over an enormous range of climates and geography, ranging from the hottest to some of the coldest regions on earth, from some of the wettest to the driest, from the equator to sub-polar latitudes and from low altitudes to some of the highest places on earth. Consequently, the climatic interactions with livestock production systems and the array of possible changes in climate are large, requiring a general approach in this review. The review will briefly address some of the core dimensions of expected impacts from climate changes and associated carbon dioxide (CO_2) increase and then some broad adaptation categories that may be needed to address negative impacts and take advantage of opportunities arising from these changes. We do not try to address impacts and adaptations across value chains, in relation to international trade or in relation to broadscale land use change as these are beyond the scope of this paper.

Livestock production regions and climate changes

Whilst grasslands-based livestock production systems are found on every continent except Antarctica, there are strong concentrations of livestock in the mid-latitudes, in the eastern USA and Europe, in eastern and southern South America, in India and China and to a lesser extent across sub-Saharan Africa (FAO 2013). The core climate changes that are likely to affect grasslands-based livestock production systems in these regions include:

- global increases in temperature averages and high temperature extremes, and based on recent experience, in some mid-to high latitude regions (somewhat perversely) increases in frequency of low temperature extremes due to increased intrusion of colder, more polar air masses. This would suggest that increases in daily and multi-day temperature variability are possible and emerging in the current record. Rates of temperature increase broadly are likely to be greater at higher latitudes and also greater in continental locations and but lesser near the coasts (IPCC 2007).

- changes in rainfall means, seasonality and increased rainfall intensity. Very broadly, rainfall averages are likely to increase in the equatorial and the cool temperate regions and decrease in the sub-tropics and mid-latitudes (IPCC 2007). Increases in rainfall intensity are expected in all regions as a function of changes in the moisture-holding capacity of the atmosphere as it warms and increased convective storm activity in some regions. Rainfall seasonality could change, particularly in the mid-latitudes with a relatively higher proportion of rain occurring in the summer months (Feng *et al.* 2012). In relation to interannual rainfall variability (a key livestock systems factor in many regions), there are already changes in key climate drivers such as the sub-tropical ridge, cyclones, ENSO, land-surface feedbacks and enhancement of the hydrological cycle which are not well-simulated in GCMs (Christensen *et al.* 2007; Hegerl *et al.* 2007; Kent *et al.* 2011; Durack *et al.* 2012; Guilyardi *et al.* 2012; Ramirez-Villegas *et al.* 2013) contributing to systematic underestimation of climate variability (Ramirez-Villegas *et al.* 2013). These collectively contribute significantly to the uncertainty of future projections (Hallegatte 2009; Wilby *et al.* 2009) with little likelihood of resolution in the near term (Hallegate 2008; 2009).
- vapour pressure deficit (the 'absolute dryness of the air') is likely to increase on average due to higher temperatures and the exponential nature of the saturated vapour pressure curve (IPCC 2007).
- solar radiation is likely to change as a function of changes in rainfall and cloudiness, with increases where conditions become drier and vice versa (IPCC 2007).
- In contrast with the regionality of expected climate changes, carbon dioxide is a well-mixed, long-lived gas in the atmosphere and so concentrations will be effectively similar across the globe, with current trajectories of change exceeding most of the IPCC emission scenarios (*e.g.* Peters *et al.* 2012).

In the longer–term, if grassland livestock managers do not adjust their land and forage management practices to suit the changed climate conditions, then risks of land degradation may increase and/or new opportunities may be lost (McKeon *et al.* 2004; Moore and Ghahramani 2013).

Impacts of climate changes on grasslands-based livestock systems

Changes in atmospheric concentrations of greenhouse gases will affect grazing systems through complex interactions involving effects on plant growth, rising temperatures, changing climate, grazing management and a potentially wide range of indirect impacts that may affect vegetation, natural resources and animal production (see Soussana *et al.* 2013). The most direct of these influences will be heat-related impacts on livestock and the ways that changes in the quantity and quality of forage affect livestock performance. We consider some of the key management issues that graziers will have to address: (1) management of heat stress; (2) forage productivity and quality; (3) vegetation composition (including weeds and fire management); (4) soil degradation; and (5) animal husbandry and health (especially pests and disease). We also briefly cover some broader issues. In the second half of the paper we then discuss approaches to dealing with each of these challenges, and adaptive strategies to ensure that pastoral enterprises remain productive and viable.

Heat stress

Metabolic heat production of livestock is closely related to forage intake. Livestock need to shed this heat to maintain stable internal temperatures and increasingly productive livestock means more metabolic heat needs to be transferred to the environment. In humid environments where there is substantial heat gain from either high temperatures or solar radiation or both (sometimes integrated into indices such as the THI (temperature-humidity index)), this transfer becomes increasingly difficult either as sensible heat or latent heat through evaporation. This tends to reduce animal intake (*e.g.* Gaughan *et al.* 2010), thus reducing production. Heat stress in livestock is thus already a key issue in tropical environments (Nwosu and Ogbu 2011; Sejian 2013) and there is an expectation that climate change will substantially increase the frequency of heat stress days, reducing livestock productivity, decreasing reproductive rates, increasing susceptibility to pests and diseases, and increasing concerns about animal welfare in particular in locations where grazing populations are concentrated, such as feedlots (Howden and Turnpenny 1997; Howden *et al.* 1999a; Mader and Davis 2004; Amundson *et al.* 2006; Nienaber and Hahn 2007, Gaughan *et al.* 2010, Hoffman 2013). There is evidence of increasing THI already in some regions (Nidumolu *et al.* 2013) and that this may in some cases already be impacting on animal performance (Petty *et al.* 1998).

Livestock water requirements will increase as temperatures warm and adequate water supplies could become particularly important when livestock are suffering heat stress both through increased intake as well as for use for cooling. Adequate water intake in hot conditions enables cooling via evaporation via panting or from skin surfaces. Consequently, when water is available, animals increase water intake considerably under hot conditions, whilst heatwave conditions can result in even greater sensitivity. For example, Gaughan *et al.* (2010) measured an increase of approximately 50% (from 40 l/day to 60 l/day) water intake of feedlot cattle with approximately a 3^{o}C increase in daily maximum temperatures. Increased water demand under climate change will also mean that livestock will be unable to travel as far from watering points, limiting use of the grazing resource in extensive grazing operations and tending to increase grazing pressure and risks of soil degradation near watering points. Impacts of increased water demand on livestock will be particularly problematic in situations where water quality is poor due to high salt concentrations, as this limits potential water intake.

Forage productivity and quality

Livestock performance depends to a large extent on the availability of young, digestible plant material (Mannetje 1974; Ash *et al.* 1982), which is determined by the frequency and duration of climate conditions suitable for plant growth (*e.g.*, McKeon *et al*. 2008). Projected changes in rainfall regimes, rising temperatures and higher levels of atmospheric CO_2 will all alter patterns of plant growth and pasture productivity, thus impacting on livestock production and grassland systems (see reviews by Wand *et al.* 1999; Campbell *et al.* 2000;, Nowak *et al.* 2004; Tubiello *et al.* 2007; Stokes and Howden 2010; Soussana *et al.* 2013 this volume) and will be very briefly summarised here.

Changes in the amount of rainfall are likely to be the major driver for net changes in pasture growth, sward dynamics and the proportion of palatable grasses in many of the world's grasslands as many of these systems are water-limited for at least part of the year (*e.g.* Izaurralde e*t al.* 2011). In addition, changes in the temporal distribution of rainfall may reduce rainfall effectiveness in regionally–specific ways, through increased variation within seasons (fewer, more intense rainfall events) and from year to year (more frequent and possibly more intense droughts). Modelling studies suggest that pasture growth responses will often amplify changes in rainfall, so that the magnitude of change in forage production will exceed the percentage change in rainfall and this will multiply again when considering economic metrics such as profitability (*e.g.* Crimp *et al.* 2002; Hall *et al.* 2008; Moore and Ghahramani 2013). For example, in a simulation study of climate change impacts on grassland livestock systems in southern Australia, Moore and Ghahramani (2013) found that the ratio of above-ground net primary production (ANPP) to rainfall change was greater than unity at 18 of 25 locations analysed, with this ratio being higher at lower rainfall sites and at intermediate temperatures. The subsequent changes in ANPP from historical values varied widely between GCM projections but averaged -9% in 2030, -7% in 2050 and -14% in 2070. However, operating profit (at constant prices) changed by an average of -27% in 2030, -32% in 2050 and -48% in 2070. The scale of these changes was such that operating losses were calculated for 9 of the 25 locations by 2070 with these losses concentrated in drier locations. The authors consider that this amplification of ANPP reductions into larger profitability declines is likely to generalize to other extensive livestock systems and will be greatest in lower rainfall locations. Several other studies have demonstrated the sensitivity of pasture production to small changes in climate (Scanlan *et al.* 1994; Johnston *et al.* 1996) and non–linear responses to rainfall (Hall *et al.* 1998). In addition, river flows respond to rainfall changes in highly non-linear ways, with amplifications of change in rainfall by factors of 2 to 3 (*i.e.* a 1% loss in rainfall can result in a 2 to 3% loss in river flow) in many environments typical of grassland livestock systems (Chiew *et al.* 2006). Consequent changes in river flow regimes and beneficial flooding may alter the production of locally–important ephemeral pastures on floodplains (White 2001).

Rising temperatures could benefit pastures in cooler climates by increasing the length of the growing season with possible reductions in frost damage. However, increased plant growth in the cooler months can deplete soil moisture at the expense of subsequent pasture growth in the spring with the net effect highly situation-dependent. In warmer climates, increased high temperature conditions foster desiccation and reduction in forage quality. Higher temperatures can also reduce pasture production through increased vapour pressure deficit and evaporative demand in conjunction with changes in seasonality of pasture growth reducing the proportion of rainfall that gets transpired by the grasslands (Moore and Ghahramani 2013). Increases in transpiration efficiency arising from the effects of elevated atmospheric CO_2 concentrations could partly offset this effect. In their study in southern Australia, Moore and Ghahramani (2013) found that ANPP will decrease with increasing temperature at 18 of the 25 locations assessed. The sites with increasing ANPP are those with both low annual temperatures and relatively high annual rainfall.

The most certain aspect of climate change is that rising atmospheric CO_2 is affecting and will further affect grassland ecosystems even in the absence of rainfall and temperature changes (see review by Tubiello *et al.* 2007). In water–limited grasslands, CO_2 will mainly affect plant growth through changing patterns of plant water use. Experiments on the C_3 (temperate) pasture component responses to CO_2 found that the higher plant production largely arose from the indirect effects of moisture savings, rather than directly–stimulated photosynthesis (Volk *et al.* 2000; Niklaus *et al.* 1998). There is also growing evidence that C_4 (tropical) grasses may not be substantially less responsive to CO_2 than C_3 grasses, particularly under field conditions (Morgan *et al.* 2004; Owensby *et al.* 1993; Stokes and Ash 2006). The effect of CO_2 in stimulating pasture growth may be greatest in ecosystems receiving intermediate amounts of rainfall (about 500 – 1000 mm/yr, depending on latitude) (Nowak *et al.* 2004; Stokes and Ash 2006) where water is intermittently limiting during most periods of active plant growth. There are strong interactions of pasture responses to CO_2 with other variables such as temperature, soil moisture and soil nutrient availability, especially nitrogen (Fischer *et al.* 1997; Suter *et al.* 2002). Consequently, the influence of CO_2 on pasture growth under field conditions, while still existing in both moist temperate (Campbell *et al.* 1997) and arid (Smith et al. 2000) conditions, can be quite variable (Nowak *et al.* 2004). The impacts of elevated carbon dioxide can have significant flow on effects to ecosystem processes such as soil carbon and nutrient cycling and soil fauna activity (*e.g.* Yeates *et al.* 2003). The effects of CO_2 have yet to be properly incorporated and validated in grassland system models as this is a challenging task due to the large-scale diversity of such systems and highly variable species by environment responses to elevated CO_2, nevertheless the broad system responses can be well simulated by relatively simple model changes (*e.g.* Howden *et al.* 1999).

Climate and atmospheric changes are likely to affect grassland livestock nutrition through three key aspects of forage quality: energy supply (non–structural carbohydrate), protein (nitrogen) content and digestibility. These forage attributes are affected by climate both directly, and indirectly through altered phenology of pasture growth (since forage quality declines as leaves age and cure).

Elevated levels of atmospheric CO_2 changes forage quality through declines in forage protein content (Wand *et al.* 1999), and increased forage non–structural carbohydrates in C_3 species (Wand *et al.* 1999; Lilley *et al.* 2001) although this does not occur with C_4 species (Wand and Midgley 2004). There is also decreased digestibility of tropical grasses, although there may be little change in digestibility of other species (Lilley *et al.* 2001). Warmer conditions tend to significantly decrease non–structural carbohydrate concentrations (and digestibility in tropical species) while also slightly reducing leaf protein content (Wilson 1982). In addition there will be changes to seasonal patterns of variation in forage quality as discussed previously. Altered seasonal patterns of variation in forage protein and utilisable energy will have consequences for ruminant nutrition (Beever 1993), but the combined effects of these interacting climate change influences has yet to be determined. In some situations the increase in digestible energy content will dominate (*e.g.* in energy-limited systems) while elsewhere the effect of decreased protein content will dominate (*e.g.* nutrient limited systems) (Howden *et al.* 2008).

Vegetation change

Climate change, in combination with management (such as responsive grazing strategies, burning, presence or absence of tree regrowth control, applied nutrients and herbicide use), can have major impacts on grassland species composition as demonstrated by past climate events (*e.g.* McKeon *et al.* 2004). As climate changes it will be essential to maintain nutritious and productive pastures to take advantage of good growing seasons, perennial grasses and shrubs to provide dry season and drought feed, fuel for fires where appropriate, and surface cover to protect soils (*e.g.* Moore and Ghahramani 2013; Webb *et al.* 2012). It is not known how most existing species will respond to unprecedented extremes of temperature and desiccation, or how this will, in detail, interact with elevated CO_2 concentrations, so changes in vegetation will have to be monitored in order to adapt appropriately.

Rising CO_2 will affect pastures by preferentially enhancing the competitiveness of plants such as legumes and grasses with high nitrogen efficiency (Soussana *et al.* 2013, this volume). It could also change patterns of soil moisture availability, interacting with increased rainfall intensity (Kulmatiski and Beard 2013) to increase the availability of moisture deeper in the soil profile (Gifford *et al.* 1996), leading to increased competitiveness of deep–rooted woody plants and legumes (Archer *et al.* 1995; Stokes and Ash 2006). In some ecosystems, increased drought stress may limit germination and establishment of woody species, thus reducing the likelihood of shrub encroachment (Lohmann *et al.* 2012). In mid-latitude pastures with mixed C_3 and C_4 grasses, rising temperatures may favour an increase in C_4 species, which generally provide a less nutritious forage than C_3 grasses (Cullen *et al.* 2008).

Changing fire regimes due to climate changes could also influence vegetation, particularly the balance between woody plants and grasses (Eldridge *et al.* 2012). Climate change could affect fire regimes in several ways. Any changes in pasture production (discussed above) will affect fuel loads, unless utilization levels by livestock are adjusted to match changes in grass growth. Pastures could also cure earlier under warmer climates, shifting the timing of fires to earlier in the season, and increasing the potential for fewer, more intense fires later in the season, increasing the risk of wildfires and making managed burns more difficult to control. From a management perspective, there may be an increasing requirement to use fire as a tool to control the possible increase in woody vegetation and other invasive species arising from climate change (Howden *et al.* 2001).

Soil degradation

Soil degradation processes such as erosion and salinisation are strongly influenced by soil hydrology and, consequently will be impacted by a changing climate. Changes in ANPP, increases in dry spells and in the seasonality of growth can potentially increase the frequency of periods when ground cover drops below thresholds needed to reduce erosional processes (Moore and Ghahramani 2013). This may interact with likely increases in rainfall intensity to significantly increase the risks of soil erosion (McKeon *et al.* 2004; Smith and Olesen 2010). This risk is likely to be further exacerbated by an increase in variability in yearly rainfall, creating a greater chance of erosion events where a wet year (high runoff) follows a drought (when plant cover is low and soils become highly susceptible to erosion). Even slight erosion of surface soils can reduce infiltration and remove a large proportion of important soil nutrients, thus markedly reducing potential pasture productivity (McKeon and Hall 2000). Hence, soil erosion may become an increasingly challenging management consideration as the climate changes. Wind erosion is also a consideration in the drier grassland environments and whilst there remains no clear indication of changes in this as a function of climate change, the risk of erosion events and severity may increase due to possible changes in ground cover as above.

An increased risk of soil salinisation will be influenced by changes in rainfall as well as by the effect of rising CO_2 levels on plant water uptake and use; however, the combined effects of these influences on hydrological processes in grasslands has yet to be broadly evaluated. More optimistic, though, is the growing interest in bio-sequestration of carbon in grassland soils (particularly in moderately–degraded soils where it may be most feasible to restore depleted carbon stores) is raising awareness of the multiple benefits of managing grasslands to maintain and improve soil health.

Pests and diseases

The effects of climate on important livestock diseases and pests and their impacts on production and animal health have been recognised and researched for decades giving rise to some understanding of the implications of climate change for some pests and diseases (McLeod 1995; Sutherst 1990; Sutherst *et al.* 1996). Livestock production from grasslands is at risk of a significant expansion in the range of pests and disease that is projected under a changing climate, particularly a shift of tropical species towards the poles (Sutherst 2001). For example, projections undertaken over a decade ago indicated a pole-ward expansion in distribution of the insect vector of blue–tongue disease, *Culicoides sp.* (Sutherst 2001). There was a significant outbreak of this disease in Europe in 2006, with the outbreak largely being attributed to climate factors (Guis *et al.* 2012). Subsequent assessments have concluded that there is an increase in the future risk of blue-tongue emergence across most of Europe due to climate change, with uncertainty in rate of this but not in the trend (Guis *et al*. 2012). Similarly, cattle ticks (*Boophilus microplus*) in Australia may also spread poleward with substantial projected production losses, and increased costs of trying to maintain quarantine and control measures (White *et al.* 2003).

Adaptation to climate impacts

An adaptation framework

The potentially significant impacts of climate change on grassland systems over the next decades are likely to interact with a large range of other decision-drivers such as changes in prices of inputs to and products from grassland systems, changes in consumer preferences, alterations in the broader societal expectations of farmers and farmlands (*e.g.* in terms of biodiversity, carbon sinks and other ecosystem services) amongst many others. All of these changes have significant uncertainty as to their form, degree and timing. Consequently, rather than an approach which tries to predict the aggregate changes, we argue that it is important to develop effective adaptive management and adaptive governance systems that operate across scales (*e.g.* Nelson *et al.* 2008), to develop an array of technological and managerial options that can address the wide range of future possibilities (Howden *et al.* 2007), to develop the adaptive capacity and managerial ability to make and implement effective adaptation decisions (Nelson *et al.* 2010 a, b; Crimp *et al.* 2010) and to develop effective learning systems that are inclusive of change and uncertainty (Stone-Jovicich *et al.* 2013).

Adaptations to climate change can be thought of as: (1) incremental changes to existing grassland systems; or (2) more systemic changes which bring new components to (or remove old components from) these systems, often with the goal of increasing diversification and hedging against new, unknown risk (Howden *et al.* 2010). These are part of a spectrum of levels of adaptation to climate changes. They are not unreasonable as first adaptation steps as they build from existing infrastructure, practice, technologies and knowledge, largely fit within existing institutional arrangements, often conform to cultural and social norms, are reasonably quick and easy for graziers to evaluate and involve limited risk, investment and complexity to manage (Rickards and Howden 2012). However, various analyses suggest that such adaptations will become less effective above temperature increases of 2^{o}C (Easterling *et al.* 2007; Howden *et al.* 2007; Challinor *et al.* 2013) requiring further, transformative adaptation (Howden *et al.* 2010; Park *et al.* 2012; Kates *et al.* 2012). Furthermore, in areas with strongly climate-affected agriculture, there are already examples of agricultural industries and enterprises making more transformative adaptations in response to existing climate changes or perceptions of future changes (Park *et al*. 2012). In these cases, transformational adaptation has been as much about seeking opportunity as it has been about avoiding threats. Hence these adaptations are intended to be ‘low regrets’ strategies. They are characterized by either changes in goal (resulting in a major change in land use and/or employment, for example) and/or changes in location (of an agricultural activity and/or farmers).

Transformational change in agriculture is not new: the planting of biofuel crops instead of food crops, the replacement of subsistence-based agriculture with modern science-based agriculture, or migration in the face of extreme drought being a few examples amongst many (Rickards and Howden 2012). What does seem to be new is that transformational adaptations to climate change are being taken pro-actively with at least a partial recognition of the intersection of climate drivers with broader change processes, in the landscape and socioeconomically, technically and politically.

Large scale changes often incur additional risk and cost and given uncertainties in trajectories of future climate change, transformational adaptation may be maladaptive or may be seen as ‘over-adapting’. This being particularly so given the long-lead times and uncertainty associated with climate change. There is at least one case in Australia where the transformative adaptation has been reversed (Jakku *et al.* 2013). Consequently, transformational adaptation has been framed as not a single step but rather a continuing process which may reverse, or may become the new ‘normal’ and then undergo incremental change before being further transformed (Park *et al.* 2012). Key costs that need to be considered for transformational adaptation include transaction costs which is the toll on resources (mental, emotional, physical, financial and social) that the process of change exacts, opportunity costs including those associated with path dependency and costs of unintended consequences (Rickards and Howden 2012).

Transformative adaptation is likely to occur more successfully with graziers, industry and regions that have significantly greater adaptive capacity, particularly managerial capacity (Park *et al.* 2012). Building these capacities may be one area where policy can enhance prospects for transformation, providing an environment where the vision of adaptation to climate change is not limited by the agricultural system as it is now, but rather by how it could be.

The following sections address some specific adaptation options for grasslands systems for the impact areas covered above (*i.e.* heat stress, forage productivity and quality, vegetation change, soil degradation, pests and diseases), then some aspects relating to maladaptation and larger-scale enabling factors. These are summarized in Table 1. Many of these are similar to best practice for the industry, but climate change is likely to put a premium on getting them right (Howden *et al.* 2001). We do not try to address impacts and adaptations across value chains, in relation to international trade or in relation to broadscale land use change.

Adapting for heat stress

Adaptations to heat stress for a given livestock systems can be classified into four main approaches: altering the

Table 1: Summary of climate change adaptation options for the grazing industry (Stokes and Howden, 2010)

Adaptation option
Broad scale adaptation
Modify existing Federal and State Drought Schemes to encourage adaptation
'Mainstream' climate change considerations into existing government policies and initiatives, *e.g.* Greenhouse challenge, salinity, water quality and Landcare activities
Work with the pastoral industry to evaluate potential adaptive responses to the system–wide impacts of a range of plausible climate change scenarios
Continuously monitor climate change impacts and adaptation responses adjusting actions to support and ensure effective and appropriate adoption
Grazing and pasture management
Introduce responsive stocking rate strategies based on seasonal climate forecasting
Progressively recalculate and adjust safe stocking rates and pasture utilization levels taking into account observed and projected climate change
Accept climate–induced changes in vegetation and modify management accordingly
Make greater use of strategic spelling
Improve on–property water management, particularly for pasture irrigation
Improve nutrient management using sown legumes and phosphate fertilization where appropriate
Develop software to assist pro–active decision making at the on–farm scale
Expand routine record keeping of weather, pest and diseases, weed invasions, inputs and outputs
Diversify on–farm production and consider alternate land uses
Managing pests, diseases and weeds
Improve predictive tools and indicators to monitor, model and control pests
Increase the use of biological controls (with caution)
Incorporate greater use of fire and alternative chemical and mechanical methods for controlling weeds and woody thickening
Livestock management
Select animal lines that are resistant to higher temperatures but maintain production
Modify timing of mating, weaning and supplementation based on seasonal conditions
Provide extra shade using trees and constructed shelters

environment that the livestock experience, managing nutrition, selection for productivity under thermal stress, and adoption of a new species that is more suited to the emerging environment (Renaudeau *et al.* 2010). Some adaptations include aspects of more than one of these.

For some livestock operations such as stockyards and feedlots and in more intensive production systems, alterations of the environment through the construction of shading, water sprinklers or misters or pad cooling facilities may be an economically feasible adaptation measure. Nidumolu *et al.* (2010) recently compared THI of several actual livestock enterprises in eastern Australia with treatments of shade, water sprinklers and in open conditions. They found that the shade treatment was very successful in preventing the extreme THI conditions that are known to reduce livestock production. The water spray treatment was only moderately successful and in some instances served to increase the frequency of 'modest' and 'moderate' heat stress. Gaughan *et al.* (2010) undertook a study of the effects of shaded treatments (versus an open-area control) in a feedlot situation and found that compared with the control, shade reduced internal body temperature during a heatwave, increased dry matter intake during this period and reduced animal stress as measured by mean panting scores. Importantly, over the 120 day experiment, cattle under the shade had greater performance (including higher final bodyweight) and had higher feed conversion efficiency. However, the shade treatment did not completely eliminate the impact of high heat load. In more extensive systems, shade may be provided by strategic development of shrub or tree cover, keeping in mind that in some grassland systems this can impact on forage productivity via tree-grass competition.

Nutritional management to reduce heat load in intensive livestock systems could include changes to feeding frequency and time of feeding, and changes in ingredients such as addition of dietary fat to increase energy density, or adding roughage to diets to reduce heat increment. Recent research on additives such as chromium and betaine indicate enhanced performance of livestock under heat stress (*e.g.* Mirzaei *et al.* 2011). This type of management response is however, unlikely to be available in extensive grassland grazing systems or in many developing country contexts. In these situations adaptation strategies such as modifying the timing of mating could also serve to match nutritional requirements of cow and calf to periods with favourable seasonal conditions. This means that the animal production system (cow/calf, steer trading, finishing for market) would have to become more flexible in order to accommodate potential changes to seasonal variability (McKeon *et al.* 2004), including changes in timing of supplementation and weaning (Fordyce *et al.* 1990).

Breeding-based improvement in livestock has been going on for millennia and climate change will likely need to draw on genetic resources developed for resistance to past drought, pests and diseases, low quality diets and heat stress conditions. This suggests that the practice of selecting cattle lines with effective thermoregulatory controls or adaptive characteristics within breeds, such as feed conversion efficiency and coat colour (Finch *et al.* 1984), would need to continue if current levels of productivity are to be maintained. As conditions in more poleward regions change, grassland-based livestock systems may have to increasingly rely on often-hardier breeds from more challenging environments (Hoffmann 2010). However, these hardier traits are often associated with lower productivity, fecundity and meat quality (*e.g.* Berman 2011). A gene for slick hair coat has been observed that improved heat tolerance when introduced into temperate climate breeds) but there is a lack of evidence that the hair coat in these lines is lighter than in well-fed warm climate-adapted Holsteins (Berman 2011). Similarly, the potential use of heat shock proteins as markers of heat stress may be useful when selecting animals better suited to excessively hot temperatures (Di Giacomo *et al.* 2012). Additional work is needed to assess the benefits of incorporating specific genes for heat stress resistance into mainstream beef production breeds.

Forage productivity and quality and soil cover

In those extensively–managed grasslands that are negatively impacted by climate change, there may be few options to compensate for declining pasture productivity apart from introductions of pasture species adapted to the evolving environment. Past efforts to increase pasture production in more humid rangelands have often relied on removing trees and shrubs to increase the availability of water, nutrients and light for grass growth (Burrows *et al.* 1988). However, this has been controversial and in some situations has been restricted by legislation because of the impacts on biodiversity, greenhouse gas emissions and catchment hydrology. Nonetheless, to counteract the broad trend towards woodier vegetation (Burrows *et al.* 2002; Donohue *et al.* 2013) it may become more desirable to use fire and selective thinning, to maintain current tree levels and pasture productivity. In temperate and Mediterranean grasslands the need to restore populations of native woody species, which have declined under past management, will compound the challenge of declining pasture production where the climate becomes drier (Dorrough *et al.* 2006; Pettet and Froend 2000).

Current management, and particularly rehabilitation, of pastures requires careful grazing management including conservative stocking rates, strategic spelling supplementary feeding, agistmentor responsive adjustments to stocking rates based on seasonal climate forecasts amongst other information (McKeon *et al.* 1993; Johnston *et al.* 2000; Cobon and Clewett 1999). These practices will likely become more important with climate change and will be necessary to ensure desirable pasture species establish and are maintained as species ranges shift under climate change. Similarly, careful grazing management will be required to facilitate the establishment of any introduced species. With shifts to rainfall regimes that increase the risk of soil erosion, it will become increasingly important to ensure that ground cover is maintained in grassland systems (Moore and Ghahramani 2013). It will also be necessary to redefine safe carrying capacities, pasture utilization levels and grazing management practices, and to continually review and adjust these in accord with the changing climate (McKeon *et al.* 2009).

In more intensively managed pastures there will be some additional options for maintaining forage production and quality. In temperate pastures, there is generally insufficient metabolisable energy in fodder for protein to be fully utilised. Breeding grass varieties with high levels of non–structural carbohydrates (the source of energy for the rumen) (Evans *et al.* 1996) could therefore improve forage quality, even if forage protein declines under climate change. Introduced legumes and fertilizer could also be used to increase nitrogen input to, and productivity of both pastures and livestock (although soil acidification and increased N_2O emissions need to be considered). It may also be possible to breed and sow new pastures that are better adapted to warmer temperatures and higher CO_2. In extensively managed grasslands, where these options will be less viable, pastoralists will likely have to rely on increased use of feed supplements (urea-molasses licks, phosphorus blocks or grain concentrates) and rumen modifiers to compensate for declining forage quality. In rangelands that are close to grain–producing areas it may be possible to concentrate on utilizing pasture growth earlier in the season and destock earlier, to make greater use of feedlots to finish livestock.

In an important recent study, Ghahramani and Moore (2013) assessed the effectiveness of a large range (37) of climate change adaptations singly and in combination for 25 sites across the southern Australian grasslands. These adaptations were in response to the climate change impacts identified by Moore and Ghahramanai (2013) noted earlier in this paper. They found that at 2030, increased soil fertility, adding lucerne to the feedbase, and confinement feeding in summer recovered overall profit fully at 52%, 28%, and 12% of locations when compared with the historical baseline period with most of these locations being in the high rainfall zone. When assessing the full range of adaptations to identify the most profitable option under projected climate changes, they found that these adaptations could return profitability to historical levels at 68%, 52% and 32% of the locations by 2030, 2050, and 2070 respectively. Again most of these sites were in the high rainfall zone. The corollary is that by 2070 almost 70% of locations in southern Australian grasslands will be below historical profitability levels due to climate change alone and most of the stress will be felt in the drier grassland sites. It is unlikely that any single climate change adaptation examined would return any location to profitability in the second half of the century, hence combinations of adaptations need to be addressed in future studies.

Vegetation change

Due to the lack of knowledge of the likely response of many grassland species and communities to the interactive effects of climate change and CO_2 impacts and management identified earlier (Webb *et al.* 2012) an active adaptive management approach is likely to be appropriate. This requires monitoring, informed experimentation so as to maximise learning, renewed goal setting and implementation in a continuing cycle.

Attitudes to the ‘desirability’ of existing species compositions and assessments of their suitably to the emerging climate may need changing and it may be more productive to recognise, facilitate and direct climate–induced changes in species distributions rather than trying to maintain the status quo. This may include shifts in attitudes, particularly regarding the definition and roles of ‘invasive’ (needing control) and ‘useful’ (in terms of production, environmental, biodiversity and aesthetic values) species. Woody weeds, particularly legumes in tropical rangelands, are likely to require more attention with climate change (Webb *et al.* 2012) as the conditions under which they may invade appear to be enhanced (*e.g.* Kriticos *et al.* 2003). Where pasture productivity increases with climate change, there may also be opportunities for more frequent use of fire to control woody weeds (*e.g.* Howden *et al.* 2001).

Pests and diseases

Several existing methods may be suitable for combating the spread of grasslands pests and disease under climate change including: applications of pesticide and chemicals to respond to outbreaks; area-wide management programs, vaccinations to enhance resistance to existing pests and disease; and selection of tick–resistant cattle (*Bos indicus*) in northern Australia. Pesticides could become less effective options in the future because of rising costs and resistance, so alternative options will increasingly need to be considered. Developing improved predictive tools and indicators may provide opportunities to reduce reliance on pesticides. Quantitative modelling has proved particularly useful in managing cattle ticks in northern Australia by identifying areas and periods of greatest risk. Other options that could be developed to improve management of pests and diseases include identifying opportunities to introduce more species of dung fauna (to eradicate buffalo fly larvae), encouraging greater use of traps (buffalo fly and sheep blowfly) and vaccines (cattle ticks and worms). It will also be important to improve monitoring and border surveillance to: (1) restrict the expansion of pests and diseases whose ranges are currently limited by cold temperatures (*e.g*., flies and ticks); and (2) prevent the establishment of new exotic pests.

Broader–scale considerations

Strategies for responding to climate challenges need to consider carefully the potential for maladaptations, *i.e*. situations where dealing with specific aspects of climate change could have unintended negative consequences when viewed in the broader context of land management and industry viability. For example, the benefits of introducing legumes to improve forage quality needs to be balanced against the risks of soil acidification and pasture degradeation from overgrazing of native pasture species (*e.g.* Noble *et al.* 1998). Caution also needs to be exercised in relation to introducing species/varieties that are hoped to be superior under altered climate conditions. The history of introducing 'desirable' species to grasslands has not always been successful, with some species becoming weeds, reducing biodiversity or otherwise negatively affecting ecosystem health (*e.g.* Lonsdale 1994). Likewise there are potential negative interactions between adaptation and mitigation options. For example, efforts to store carbon in grasslands will have to balance the long–term costs and benefits of changing pasture production, the effort to maintain enhanced vegetation and soil carbon stores, and the future threats of hotter and/or drier climates to enhanced carbon stores.

As the anthropogenic trend becomes more obvious from the background of natural variability the motivation for adaptation of grassland systems will likely increase. However, the adoption of new property management practices will also require: demonstration of the benefits of new adaptation options; buffering against establishment failure of new practices during less favourable climate periods; alteration of transport and market infrastructure to support altered production; continuous monitoring of climate change impacts and management responses to adjust actions and ensure effective and appropriate adaptation; and development and modification of government policies and institutions to support implementation of the required changes (McKeon *et al.* 1993; Howden *et al.* 2007).

Over the short term (perhaps the next 20 years), possible increases in the occurrence of extreme events and uncertainty over climate change trends will make risk–based adaptation approaches such as seasonal climate forecasting appealing. This will facilitate the incremental changes in management practices that land managers are likely to incorporate anyway as part of their usual business of adjusting to changing operating conditions. Such responses are likely to occur with little policy intervention and may include adaptations such as greater use of feed supplements, shifts to hardier animal breeds and modified herd management. Many of these options could be promoted through existing initiatives that encourage improved management of natural resources in grasslands.

Over the longer term (20–100 years), greater government intervention may be required to support adaptation in the rangelands, particularly in those locations where the rate or magnitude of climate change overwhelms the existing capacity of local communities to respond. This may involve policy support to encourage adoption of adaptation practices and assistance of communities through the risky transition periods.

Governments, at all levels, continually develop and modify strategies, initiatives and policies to deal with environmental and socio-economic issues such as land condition, biodiversity, greenhouse gas emissions, drought, salinity, water quality, economic development, health and social cohesion amongst others. Similarly, at the property scale, grassland management practices are constantly being adapted to a continuously changing operating environment, such as changes in prices for farm inputs and products, changes in policies, programs and regulation for example on resource management, greenhouse gas emissions and animal welfare (McKeon *et al.* 1993). It will be important to identify and promote synergies with existing initiatives such as drought policy and address conflicts that create barriers to adaptation. It will also be of paramount importance that new and emerging polices enhance self-reliance and the ability of producers to respond opportunistically to changing seasonal conditions and, most importantly, do not set up frameworks that promote dependence or prescriptive 'on-size-fits-all' responses.

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