Climate change impact and adaptation in temperate grassland and livestock industries

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ABSTRACT

Climate is projected to have negative impact on temperate grassland and livestock productions across the globe. Moderately elevated atmospheric CO_2 in the near future is expected to increase plant photosynthetic rates but this is likely to be limited by soil nitrogen deficits. However, in Australia at least it is unlikely that positive effect of elevated CO_2 on plant production be able to offset the negative impacts of climate change. Currently there is a considerable gap between actual and achievable production and profit in Australian grazing systems and many management and genetic improvements for climate adaptation would operate by filling this gap. Because of likely substantial declines in efficiency frontier of grazing systems under changing climate compared to the historical climate, filling the production gap will be a more challenging task in coming decades. Research into climate change impact and adaptation in managed grasslands has been mostly limited to Europe, North America and Australasia. Large areas of managed grasslands exist in South America, China, Africa and south-west Asia for which there is little understanding of the likely impact of climate change impact and effectiveness of potential adaptation options. These grasslands are typically managed at lower intensity than European or North American systems and often form part of crop-livestock farming systems. There is a clear need for research into the direct and indirect impacts of climate change on these grasslands and on the livestock and people they support.

Key words: Climate change, Ecosystem health, Food security, Grazing system, Livestock production gap, Yield gap.

Introduction

Managed grasslands cover 25% of the global landmass and 70% of the land that is under agricultural use and carry more than 1.5 billion animal units (weighted by relative size and growth rates).This land use provides 50% of the biomass used by the global livestock population (Herrero *et al.,* 2013) which in turn is the source of 15% of the energy and 25% of the protein consumed by the global human population (FAO 2009). Anthropogenic greenhouse gas emissions are expected to lead to climate and atmospheric changes (IPCC, 2014), increases in global temperatures and consequent changes in the global water cycle over coming decades (IPCC, 2007). Increases in the frequency of drought have already been observed in some parts of world (Soussana *et al.,* 2013).According to the 5thAssessment Report of the IPCC (Stocker *et al.,* 2013), increases in the frequency, duration and magnitude of extreme high temperature sand consequent heat stresses are expected for the 21st century across the globe. For example, by 2050 a warming of about 0.8–2.8°C and decreases in rainfall of up to 20% are projected for the southern part of the Australian continent. Changes of this magnitude can be expected to significantly affect plant and animal production in this part of the world (Moore and Ghahramani, 2013a).

At the same time, elevated atmospheric CO_2 (eCO_2) concentrations are expected to have a range of beneficial direct effects on plant function (Ainsworth & Long, 2005). eCO_2 reduces sensitivity to lower precipitation in grassland ecosystems, reduces plant mortality and increases plant recovery during severe water stress events (Soussana *et al.,* 2010).

Changes in climate are expected to have a negative impact on grassland and livestock production. Surprisingly, this largest land use of global agriculture has been given little attention despite its importance for global food security (IPCC, 2014). Since the last International Grassland Congress in 2013, there have only been limited additions to our knowledge of climate change impacts on grassland and livestock industries. The 5th Assessment Report of the IPCC (Porter *et al.,* 2014) has summarized climate impacts on grazing systems and the adaptations that will be required and clearly indicated that there is a lack of research and evidence concerning these climate change impacts.

Following definition by The Intergovernmental Panel on Climate Change, we define adaptation to changes in climate as any strategy to avoid or compensate for intolerable climate risks to the production and profitability of grazing systems. Recently we have carried out a series of studies on climate change impacts in Australia on mixed-farm systems and on ways of adapting grasslands and the livestock industries to climate change. In this paper we briefly review potential impacts of atmospheric and climate change on grassland and livestock (sheep and cattle) around the globe and Australia, with an emphasis on adaptation analysis.

Impacts of climate change on grasslands

The response of grasslands to climate change is more complex than other agricultural systems such as cropping or forestry. In addition to the common responses of plant monocultures to eCO_2 and to changes in temperature and precipitation, many managed grasslands are composed of multiple plants of different functional types that their response can differ. This would result in compositional changes that can significantly affect livestock production. Legume species are commonly observed to perform relatively better than grasses under eCO_2 (Schenk *et al.,* 1995). In both subtropical and some temperate grasslands, mixtures of species with C_3 and C_4 photosynthetic pathways are found: the latter should be favoured by increasing temperature and the former by eCO_2 (Hovenden *et al.,*2008; DaMatta *et al.,* 2010).However, generalizations about the responses of grassland plant functional types to eCO_2 should be treated with caution, however. In a glasshouse study, Bolger *et al.* (1997) found that the variation of growth response to eCO_2 by grassland species of the same functional type was much greater than the mean variation between functional types. As a result, grassland compositional change under eCO_2 can be expected to depend critically on the specific species in the sward.

Plant-animal interactions and management interventions further complicate the picture. One example among many relates to predictions of "progressive nitrogen limitation" (PNL). It is observed that sequestered N in grassland soil declines progressively under elevated CO_2, so that lack of plant-available N can suppress plant responses to eCO_2. There is evidence for this process in low-input grasslands managed by cutting (Leakey *et al.*, 2009), but in grazed grasslands it may well be ameliorated by rapid cycling of N through the livestock. PNL can, of course, also be avoided through the strategic application of N fertilizer in those grasslands where increased legume N fixation in response to eCO_2 does not increase N inputs to the system sufficiently to avoid it.

Observed impacts in field experimental studies: The effects of eCO_2 on plant biophysical interactions have been widely examined around the world in free air CO_2 enrichment (FACE) studies, but only a relatively small number of studies address managed grasslands and in particular those that are under grazing. Soussana and Lüscher (2007) reviewed the effects of climate change on grassland species and found that doubling of CO_2 resulted in an increase in the rate of photosynthesis by 30-50% for C_3 species. The effects of eCO_2 on short-term photosynthetic rate appear to attenuate over longer time scales, however, Campbell & Stafford Smith (2000) stated that doubling CO_2 stimulates grassland production by 17% on average in field experiments at several sites in Australia, Europe and USA, while Tubiello et al. (2007) concluded that observed increases in aboveground production of C_3 pasture grasses and legumes are of the order of +10% and +20%, respectively.

The experiment reported by Newton *et al.* (2006) demonstrates the complexity to be expected from managed grasslands responding to eCO_2, even in the absence of changes in other climatic factors. They studied a multi-species, temperate pasture under grazing and cutting over 7 years at ambient and 475 ppm eCO_2 (i.e. approximately the eCO_2 that already entrained for 2030). Photosynthetic rates were increased under eCO_2, but it appeared that the majority of extra assimilation was allocated to roots rather than shoots. The legume content of the eCO_2 sward increased – although with species-specific interactions between eCO_2 and defoliation method (cutting or grazing) – and inputs of biologically fixed N therefore more than doubled; despite this increased N input, however, there was some evidence of progressive nitrogen depletion in soil measurements. A decrease in herbage protein content within species was compensated for by an increase in the proportion of protein-rich legume herbage. Ultimately, two different species of herbivore both performed better under eCO_2; grazing sheep were probably responding to the faster gut passage rate of legumes by eating more herbage, while the population of the root nematode *Longidorus elongatus* increased as the supply of belowground carbon increased.

Experiments studying the interactions between eCO_2 and climatic factors indicate that this complexity of response is likely to increase even further in real-world situations, where the climate will change as CO_2 concentration increases. In a French low-intensity grassland, simulated warming and summer drought projected for 2080 outweighed the effects of corresponding eCO_2, so that aboveground NPP decreased when all 3 factors were applied (Cantarel *et al.*, 2013); in this environment, it was warming rather than eCO_2 that increased the contribution of legumes to NPP at the expense of grasses. A FACE experiment on an unfertilized perennial grassland in Tasmania (Hovenden *et al.*, 2008) detected evidence of PNL similar to that found by Newton *et al.* (2006) in an eCO_2-only treatment, but when temperatures were also increased by 2°C no evidence of PNL was found; in this grassland no response of aboveground NPP to eCO_2 or warming was found.

Predicted impacts through modelling: Modelling studies predict different responses of grassland production to climate changein different regions across the globe. Rounsevell *et al.* (1996) estimated no negative impact of climate change in the near future on grasslands in England and Wales, while Riedo *et al.*, (1999) predicted even a slight positive effect on grassland productivity in temperate grasslands of central Europe. Morales *et al.* (2007) reported likely increase in ANPP (NPP) throughout Europe substantial regional variability.

Across regions in United States, mostly an increase in forage predicted under different climate scenarios (Thomson *et al.,* 2005). Parton *et al*. (1995) predicted a decrease, especially in global temperate steppes and cold rangelands while a significant increase in NPP in mesic regions and dry savannas with no net change in cold desert steppe or humid tropical regions was predicted.

For a set of locations in south-eastern Australia, Cullen *et al*. (2009) concluded that pasture production would be reduced if rainfall decreased by more than about 10%, but total pasture growth in Tasmania would be robust to rainfall declines of up to 20%. Moore & Ghahramani (2013a) modelled temperate grasslands across southern Australia and found that at sub-continental scale the projected impact of climate change depended upon the global circulation model used, with a range from an 18% decrease to a 6% increase at 2050. This uncertainty was driven by uncertainty in the rainfall projections in this mid-latitude region of the world. Projected changes in aboveground NPP at specific locations were much larger, particularly in lower-rainfall environments where major decreases were modelled.

Temperate European grasslands are predicted to see longer growing seasons under climate change (Olesen and Bindi, 2002; Juin *et al*., 2004).In North American, increased temperature is expected to lengthen forage growing season but with decrease in forage quality, with important variations due to rainfall changes which may limit water availability (Craine *et al.,* 2010; Hatfield *et al.,* 2011). In addition to experiments, modelling works also have predicted decline in forage quality under changing climate in Europe (Graux *et al.,* 2013) and Tasmania in Australia (Perring *et al.,* 2010). Cullen *et al*. (2009) also identified a shift in the pattern of pasture production in south-eastern Australia, with winter growth rates increasing under projected future climates and the pasture growing season ending earlier at the end of spring. Moore and Ghahramani (2013a) found that this general shift in the pattern of growth was widespread across southern Australia. The same study also found that legume content of grasslands was likely to increase, with larger increases at wetter locations (Moore & Ghahramani 2013b); the gross effect of increased legumes on nutritive value outweighed changes in digestibility of individual species.

More recently we have started to consider impact of climate change on managed grasslands within mixed farming systems, which are a major land use in the mid-latitudes of Australia and South America. In Western Australia, our modelling results show that fertilisation effect of eCO_2 on pasture ANPP could in part offset negative impact of changes in rainfall and temperature (combined effect with changes in temperature and rainfall)by 8% (relatively high rainfall location) to +11% (a dry location under the hot and dry potential future climate of 2030).However, the eCO_2 fertilisation effect was not enough to counteract the negative effects from changes in rainfall and temperature at drier sites. In these farming systems, avoiding soil carbon losses (and the resulting degradation of soil structure) is much more of a concern than progressive N limitation through soil organic matter sequestration; as PLN can be ameliorated by applications of N fertilizer during the cropping phase and cycle through animals.

Impact on livestock industries

Climate change impacts on livestock will be through the direct and indirect effects on grassland production described above, direct impacts of heat stress and water availability on animals, and indirect effects via livestock diseases (IPCC, 2014). Overall, a little research has been published on observed impacts of climate change on livestock systems (IPCC, 2014). Heat stress is an important limiting factor for livestock (IPCC, 2014); again, there is limited research on the direct impacts of climate change on heat stress in animals (Hahn *et al.,* 1992). It is highly likely that high temperatures tend to reduce animal feeding and growth rates (André *et al.,* 2011) with likely smaller negative impact at lower latitudes because of previous adaptation of animals to heat stress and dry conditions (Thornton *et al.,* 2009). To adapt to heat stress, a long term approach could be avoiding a single-trait livestock breeding strategy which may tend to result in animals with lower heat tolerance (Porter *et al.,* 2014). Guis *et al.* (2012) showed facilitation of ruminant diseases associated with changes in climate in Europe. This can be a limiting factor for adaptation design, however current biophysical modelling, in general, do not take animal diseases into account.

Our modelling studies in southern Australia suggest that climate change impacts on pasture growth result in amplified impacts on livestock production. Firstly, the reduced average growing season results in a lower average quality of the animals' diet in these year-round grazing systems, so reducing the optimal sustainable rate of pasture utilization even in regions where rainfall is projected to increase (Moore and Ghahramani, 2013a). Second and more importantly, the amount of ANPP that must be left unconsumed to preserve ground cover increases as the gap between growing seasons become longer, this in addition to reduction in ANPP therefore results in a larger reduction in the maximum sustainable stocking rate. We modelled increases in livestock conversion efficiency (due mainly to increased pasture legume content), but predicted that they will not be large enough to maintain income in the face of reduced pasture consumption; a reduction in gross income in turn reduces profit disproportionately because the grazing systems involve substantial fixed costs (Moore and Ghahramani, 2013a). We therefore projected declines in meat production from Australian temperate pastures at the order of 25% in the absence of adaptation measures.

Adaptations in grassland and livestock

Adaptation to climate change requires changing current practices to generate better results under the prevailing climate. It can include reducing risk and vulnerability and building the capacity to cope with climate impacts while seeking opportunities (Tompkins *et al.,* 2010), such as new condition to reducing the current gap between realised and potential production. This means filling the yield gap is an adaptation pathway. Climate adaptation options in grassland and livestock need to be adapted to changes in atmosphere e.g. elevated atmospheric CO_2, changes in climate e.g. rainfall, temperature, vapour pressure deficit, and increase in climate variability. Incremental adaptations which are applicable on a range of time scales can be autonomous within a farming system (Porter, 2014) or be on historical trend of progress e.g. animal genetic improvement (Moore and Ghahramani, 2014). While single incremental adaptations are likely to be helpful only in high rainfall regions, systemic combination of adaptations can result in substantial increases in benefits in terms of production and profit when compared with single adaptations (Ghahramani and Moore, 2015). Transformative adaptations are significant changes in current systems e.g. change in the nature, composition, and/or location of threatened systems (Smit and Wandel, 2006). Systemic adaptations may also be referred as transformative if makes substantial changes in the system.

Climate change adaptations in grazing systems can be divided into the feed base adaptations and livestock adaptations. For each of these, changes in both genetics (either through breeding or selection of existing genotypes) and to management can be adaptive. Adaptations in grassland practice will generally aim to increase ANPP (or at least ameliorate decreases) and/or minimize periods of low ground cover to reduce the corresponding risk of soil erosion. In southern Australia, a key risk that constrains livestock production is periods of low ground cover that can result in soil erosion. Ghahramani and Moore (2013) reported that at 2030 two management changes (increasing soil fertilizer rates and introducing "confinement" feeding of supplements during summer drought and one genetic change could potentially fully recover overall grazing system profitability to its historical baseline in a significant number of regions. Of course livestock systems will potentially be strengthened with multi-level strategies to minimize negative impacts (Porter, 2014; Ghahramani and Moore, 2015).

Our studies suggest strongly that in southern Australian grasslands it will be necessary to adapt stocking rates – usually downward – to avoid unacceptably high risks of soil erosion under a changing climate. Otherwise we focussed on potential livestock adaptations through genetic improvement of existing animal breeds, based on historical trends (Moore and Ghahramani, 2014): increased body size, fleece growth or and conception rate, and avoidance of heat stress. As mentioned earlier, heat stress is assumed to be an important limiting factor for livestock (Porter, 2014), but there is limited research on the direct impacts of climate change on heat stress in animals (Hahn *et al.,* 1992).Increases in livestock body size are a long-term trend, in Australia and elsewhere, which can be assumed will continue (Bell and Moore, 2012; Moore and Ghahramani, 2014). Since the maintenance energy requirements of ruminants vary with the 3/4 power of their bodyweight, while their maximum rate of intake increases roughly linearly (CSIRO, 2007), larger animals should use the energy they consume more efficiently for growth, wool production or reproduction. Also, in cattle enterprises, Worstell and Brody (1953) reported higher heat tolerance for animals with greater surface area.

Our modelling results (Moore and Ghahramani, 2014) showed that the single most effective genetic improvement depended on the livestock enterprise. In sheep enterprises it was breeding for greater rates of fleece growth, while in cattle systems it was larger body size. Increased conception rates are less effective but potentially viable as an adaptation in beef cow and crossbred ewe enterprises. In the southern Australian environments, where summers are dry, breeding for tolerance to heat stress is unlikely to noticeably improve the performance of livestock production systems, even at 2070. As with the grassland adaptations, genetic improvement of livestock would able to recover much less of the impact of climate change on profitability at drier locations where the need for adaptation is likely to be greatest (Moore and Ghahramani, 2014).

In our research we modelled livestock enterprises operating at the efficiency frontier (Keating *et al.,* 2010; Fig 1).Efficiency frontier is upper potential level of the system for production and profitability. Many farmers operate grazing systems with more conservative stocking rates and use of inputs, and for these graziers a change in management policies toward the efficiency frontier (i.e. adoption of more-intensive management practices) may be the most effective adaptation strategy. Many grazing systems are integrated with cropping and one climate adaptation in either of them can change their relationships. In Africa changes in climate with increased rainfall can be in favour of cropping (Kabubo-Mariara, 2009). In Australian dryland mixed farm systems, livestock predicted to be less sensitive to changes in climate and be a risk avoiding strategy, thus shifts towards increased livestock may be a helpful strategy in adapting to climate change and managing the associated financial risks.

Ecosystem health of managed grasslands under climate change impact and adaptation

The key environmental issues facing grassland managers vary within and between countries and regions. In high-input managed grasslands such as the perennial ryegrass-based systems of northern Europe, the main concern is losses of nutrients from the system. In such systems the effects of changing climate are likely to be masked by changes in the regulatory and financial drivers of nutrient input rates. Extra sequestration of N (in particular) in residue and soil pools may have some beneficial effects, however, by buffering peaks in N losses.

In less-intensive managed grasslands, such as those in southern Australia, different measures of ecosystem health are more important. Soil erosion can be a serious issue in some regions, e.g. Western Australia, where rainfall is low and surface soils are dry for long periods. The projected declines in ANPP and shorter growing seasons described above imply that the frequency of days with ground cover less than 70% may increase progressively over the 21st century (Ghahramani and Moore, 2015). This will result in increases in soil erosion risk (Lang and McCaffrey, 1984). Systemic adaptations aimed at increasing grassland NPP and hence profit can offset these declines in ground cover, at least to some extent (Ghahramani and Moore, 2015), although a shift to lucerne pastures may exacerbate them if it is used as an adaptation.Compositional shifts to legume dominant pastures, whether produced by plant competition or the introduction of legumes as an *adaptation*, may result in soil acidification (Haynes, 1983; Bolan *et al*. 1991).

The main greenhouse gas (GHG) emitted from grazing systems is enteric methane (CH_4) from ruminants. CH_4 is the second most important anthropogenic GHG, and ruminants are the largest source of its emissions. Ruminant CH_4 emission in grazing systems is depending on animal number (stocking rate), as climate change causes in decline in animal number, ruminant CH_4 emission intensity is expected to decrease across southern Australia in range between 1% to 12% (Ghahramani and Moore, 2015). Full climate adaptation of Australian temperate grazing system will increase stocking rate and at an efficiency frontier (Fig 1), using method from Blaxter and Clapperton (1965), ruminant CH_4 emission rate will projected to change from 70 kg ha^{-1} yr^{-1} in a baseline (1970–1999) to 84, 83, and 75 kg ha^{-1} yr^{-1} in 2030, 2050, and 2070 (Ghahramani and Moore, 2015). Higher rates of CH_4 emissions may affect profitability depending on future emissions pricing.

Overall, (i) adaptation results in increased sustainable stocking rates, (ii) emissions intensity doesn't shift all that much when maximizing profit alone.

Valuing adaptation of managed grasslands to changing climate

Adaptation options should provide resilience in farming systems and reduce variability in financial return. Effectiveness of adaptation strategies can be evaluated in comparison with their effectiveness under historical climate with the current gap between realised and potential production (efficiency frontier). Currently there is a substantial gap in production of Australian grazing systems due to more social-management constraints than biophysical. If one would like to define adaptation as capacity building to seek all opportunities in addition to that gained from changes in climate, we may evaluate effectiveness in comparison with the current climate. In our view those options count as adaptation that gain benefit from changes in climate, but however, when we apply adaptation options we also filling the gap between realised and potential production.

In a long term financial return in southern Australia and at cross-regional scale, optimization of grazing enterprises by systemic adaptation in 21 century would result in smaller profitability than optimized systems under historical climate, although would increase profitability in comparison with current systems (Fig 1). Decline in upper potential for production and profitability at efficiency frontier (Ghahramani *et al.,* 2015) projected for grazing systems of southern Australia(Fig 1).This would be 6.1% decline at 2030, 6.1% decline at 2050, and 16.0% decline at 2070 (Fig. 1). Because there is current gap, therefore optimized grazing systems are predicted to provide greater profitability even under changing climate compared to current systems. Should note that genetic improvements assumed to taken place in coming decades would offset a significant portion of negative impact by climate change (Fig. 1).Total potential economic value of adaptation (for fully enhanced future systems) added to current baseline for the livestock industries of southern Australia would be: +68.6% at 2030, +68.6% at 2050 and +50.8% at 2070 (Ghahramani and Moore, 2015). These values are assumed with current costs and prices and the full adaptability of options or at the efficiency frontier of the system which all can't be achievable. In Fig. 1, bottom line denotes to current systems under optimised stocking rate and should note that not all grazing systems are managed at this level. Thus this is greater than efficiency current of the grazing systems and adaptation value can be even larger than numbers mentioned in above.

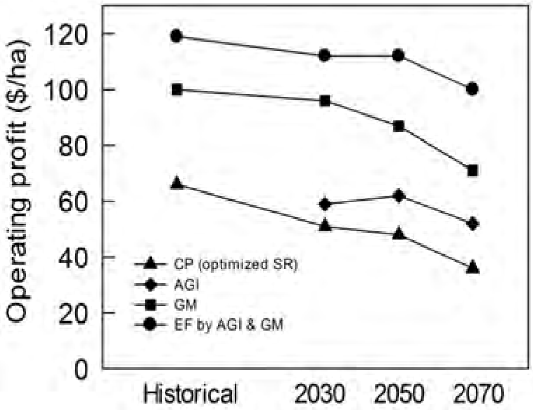

Fig.1: Modelled operating profit of southern Australian grazing systems (cattle and sheep) per ha for climate change impact and effectiveness of adaptations (with constant cost and price). Values are weighted average over area and economic contribution of each enterprise. Future climates are AR4 projections. CP: current practise, GM: grassland management, AGI: animal genetic improvement. EF: efficiency frontier by improvements in grassland management and animal genetic (only for future).

Conclusion

Despite limited observational evidence, our experience on Australian temperate grasslands indicates that climate and atmospheric change are likely to have negative impact on temperate grassland and livestock productions. In order to gain benefit from moderately elevated CO_2 on plants photosynthetic rate there would be need to maintain soil N, and this may result in needs for plants compositional changes and careful animal management e.g. manure. Currently there is a considerable production and profit gap in Australian grazing systems that can be filled by different tactical and strategic management options, incrementally or in a systemic combination. Thus, there will be capacity to increase current production, but because of decline in efficiency frontier of grazing systems under changing climate, filling the production gap will be more challenging task in comparison with current climate. Livestock systems are a well-known risk avoiding strategy under dry climate conditions and, by modelling, is likely that livestock be more risk avoiding under climate change.

Research into climate change impact and adaptation in managed grasslands mostly has been limited to Europe, North America and Australasia. The exceptions – globally-focussed studies such as that of Field *et al.* (2012) – have, perforce, not been able to take account of the diversity of grassland species and of their physiological responses to climate change drivers. Large areas of managed grasslands exist in South America, China, Africa and south-west Asia for which we have little idea of the likely impact of climate change, let alone of potential adaptation options. These grasslands are typically managed at lower intensity than European or North American systems and often form part of crop-livestock farming systems. There is a clear and present need for research into the direct and indirect impacts of climate change on these grasslands and on the livestock and people they support.

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