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Managing Grassland Systems in a Changing Climate: The Search for Practical Solutions

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Managing grassland systems in a changing climate: the search for practical solutions

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Abstract. By the end of the XXI[st] century, a global temperature rise between 1.5 and 4°C compared to 1980-1999 and CO_2 concentrations in the range 550-900 ppm are expected, together with an increased frequency of extreme climatic events (heat waves, droughts, and heavy rain) that is likely to negatively affect grassland production and livestock systems in a number of world regions. Grassland management has a large potential to mitigate livestock greenhouse gas emissions at a low (or even negative) cost, by combining a moderate intensification, the restoration of degraded pastures and the development of silvo-pastoral systems. Climate change vulnerability will be highest in regional hot spots with high exposure to climatic extremes and low adaptive capacity, such as extensive systems in dryland areas. Biome shifts, with expansion or contraction of the grassland biome, are projected by models. Resistance, resilience and transformation strategies can be used for grassland adaptation. With sown grasslands, adaptation options include changes in forage species (*e.g.* use of C_4 grasses and of annual species) and genotypes and the use of grass-legume mixtures. Grazing management can be adapted to increase the resilience of plant communities to climatic variability. Our understanding of the synergies and trade-offs between adaptation and mitigation in the grassland sector is still limited and requires further research. Provided this understanding is gained, climate smart grassland systems that sustainably increase productivity and resilience (adaptation), reduce greenhouse gas emissions (mitigation), and enhance food security and development could be promoted. By reducing productivity gaps and increasing livestock production efficiency, they would also contribute to mitigate climate change from tropical deforestation and expansion of grasslands into savannahs.

Keywords: Climate change, pasture, livestock, adaptation, greenhouse gas, mitigation.

Introduction

The grassland biome, which corresponds to a permanent herbaceous vegetation used by wild and domestic herbivores, covers about one-quarter of the earth's land area (Ojima *et al.* 1993). Grasslands are currently estimated to contribute to the livelihoods of over 800 million people (Reynolds *et al.* 2005) and provide a range of goods and services to support flora, fauna and human populations. Except within eco-geographical regions where vegetation is maintained by climate and soil factors at herbaceous stage, most of the grasslands around the world are the result of livestock management avoiding encroachment by shrubs and trees (Lauenroth, 1979; Lemaire *et al.* 2005). Humans utilize about 40% of the Earth's net primary production (Rojstaczer *et al.* 2001). Grazing and fodder would represent half of this global appropriation by humans of plant productivity *(Karlheinz Erb, Institute of Social Ecol. Vienna, pers. com.).*

Livestock production systems emit 37% of anthropogenic methane (Martin *et al.* 2009) most of that from enteric fermentation by ruminants. Moreover, they induce 65% of anthropogenic nitrous oxide emissions, the great majority from manure (FAO, 2006), and 9% of global anthropogenic CO_2 emissions. The largest share (*i.e.* 7%) of this CO_2 emission derives from land-use changes – especially deforestation – caused by expansion of pastures and of arable land for feed crops. Nevertheless, the global soil organic carbon sequestration potential is estimated to be 0.01 to 0.3 Gt C/year on 3.7 billion ha of permanent pasture (Lal 2004). Thus soil C sequestration by the world's permanent pastures could potentially offset up to 4% of the global green house gas (GHG) emissions. This could be achieved through grazing land management and restoration of degraded lands (Smith *et al.* 2008). Reducing excessive nitrogen (N) fertilization and the substitution of mineral N fertilizers by biological N fixation, as well as improved nutrition of domestic ruminants to reduce methane from enteric fermentation and improved manure management can also play a significant role (Smith *et al.* 2008).

For the first time, the atmospheric CO_2 concentration has reached in May 2013 a level of 400 ppm at the Mauna Loa station in Hawaï, indicating a +85 ppm increase after 55 yrs of continuous measurement. The current level of atmospheric CO_2 is the highest experienced by the biosphere since at least 800,000 yrs and the current mean global temperature is slightly above the temperature range experienced during the Holocene, which has seen the onset and expansion of agriculture since ca. 10,000 yrs BP (Marcott *et al.* 2013). By the end of the 21st century, the biosphere will be experiencing unchartered conditions with a temperature rise between 1.5 and 4°C compared to 1980-1999 and CO_2 concentrations in the range 550-900 ppm (IPCC 2007). Until recently, it was expected that despite climate change and increasing world population, there would be several decades with food surplus – and low prices – ahead (IPCC 2007). Nevertheless, food insecurity has increased in the context of the inter-linked food and economic crisis since 2008. Actions taken so far are not sufficient to overcome the crisis, let alone reduce the chronic food and nutrition security problems (Von Braun 2008).

Grassland production is intimately linked to climate conditions and therefore highly exposed to climate change. Short-term natural extremes such as storms and floods, inter-annual to decadal climate variability (such as the El Niño) have significant effects on crop and pasture production (Tubiello *et al.* 2007). Between 1980 and 1999, severe droughts have caused mortality rates in national herds of between 20% and 60% in several arid sub-Saharan countries (IPCC 2007). Again, in 2009-2011, droughts triggered a looming humanitarian and food crisis in some countries, which would affect more than 10 million people across the region.

The climate system is already moving beyond the patterns of natural variability. The extreme drought and heatwave that hit Europe in the summer of 2003 was unprecedented since at least 1500. It caused a green fodder deficit of up to 60% in affected countries like France. In Switzerland fodder had to be imported from as far away as Ukraine. In the USA, heatwaves in 2005, 2006 and 2007 broke all-time records for high maximum and minimum temperatures, and drier than average conditions were reported for more than 50% of the conterminous United States in 2000–2002, 2006–2007 and 2012. In Australia, the widespread six-year drought from 2001 to 2007 is considered the most severe in the nation's history

A further drying of large parts of the subtropics is likely by the end of this century (IPCC 2007a). Amplification of the hydrological cycle as a consequence of global warming is forecast to lead to more extreme intra-annual precipitation regimes characterized by larger rainfall events and longer intervals between events (IPCC 2007a). Unless major adaptations are made, high seasonally averaged temperatures will challenge food production in the future. Global climate change can be expected to threaten food supply through changing patterns of rainfall and increasing the incidence of extreme weather, leading to greater variability of grassland production, but also increasing price volatility and contributing to changes in trade flows (Lobell *et al.* 2008). It is highly likely (more than a 90% chance) that by the end of the 21st century, growing season temperatures in most of the tropics and subtropics will exceed even the most extreme seasonal temperatures recorded from 1900 to 2006 (Battisti and Naylor 2009). For instance, in Europe, in the next 40 years, the risk of summers as warm as 2003 may increase by two orders of magnitude and may approach the norm by 2080 under high emission scenarios.

In this review, we first set the scene by sketching global trends in the livestock sector for a range of socio-economic storylines and climate change scenarios and we discuss how climate change impacts on grasslands could affect the sector. We then review the impacts of climatic and atmospheric change on grasslands and we provide a series of examples concerning likely regional hot spots. Finally, we review the scope for adaptation and for practical management solutions that would also increase soil carbon sequestration and mitigate greenhouse gas emissions. We conclude by key priorities for grassland science in this area in future years.

Setting the global scene

Within the European Commission AnimalChange project (www.animalchange.eu), we have analysed the development of the livestock sector and of grassland production since 1961. Feed mixes (including grassland use) and feed conversion efficiency were calculated for global dairy and meat production systems for the reference year 2005 based on the report by FAO (2013). Past changes since 1961 were back cast using the AgRipe (Agricultural Representative Pathways and Emissions) framework (Ben Ari *et al.* in preparation), which relates the demand and supply of food and feed and the agricultural GHG emissions. We then analyzed the projections of a coupled biophysical partial equilibrium economic model (Globiom, Havlik *et al.* 2011), which simulates changes in the livestock sector for each of the three SSPs.

Estimates of the global net primary productivity (NPP) of grasslands and rangelands have been derived from satellite measurements. FAO (2006) reported a mean global grassland NPP of 1046 g C/ m^2/yr. Assuming that half of plant productivity is partitioned above-ground and that ca. 30% of this above-ground growth can be ingested by grazing, the potential herbage use would reach 173 tons C/ km^2, that is 433 tons DM/km^2 (assuming a 40% carbon content). However, only a small fraction (*ca.* 16 %, FAO, 2013) of this potential appears to be effectively used by ruminants, as a consequence of an insufficient digestibility and quality, especially in degraded pastures, and of a short duration of use of some of the pastures (*e.g.* in open ranges from mountain areas and dry areas which are often used sporadically). In 2005, on a protein basis, 58 and 70% of the total feed ingested by dairy cattle and meat animals, respectively, came from grasslands. On a global scale, total feed conversion efficiency (tons animal proteins production per tons of total plant proteins ingested) of global dairy and ruminant meat production systems was estimated at 0.119 and 0.057, respectively (Ben Ari *et al.* in preparation).

Based on this calibration for the reference year 2005, calculations with AgRipe allow back casting trends in the sector over 1961-2005. During this time period, the fraction of grassland herbage in the diets of domestic ruminants declined by 3.4% per decade, while the average ruminant feed conversion efficiency increased by 8% per decade (Ben Ari *et al.* in preparation). These changes reflect the intensification of livestock production, through an increase-ing proportion of arable feed (including food crop grains, crop residues and fodder) in diets and improvements in husbandry and breeding that together raised feed efficiency. Interestingly, this rise in feed conversion efficiency reduced the direct (not including emissions induced by land use change and inputs) GHG emissions of the global livestock production per unit animal protein by 23% over 1961-2005. Nevertheless, direct GHG emissions from the livestock sector increased by 85% over 1961-2005, due to the sector's rapid growth. (Ben Ari *et al.* in preparation).

The FAO projects a large increase in demand for both dairy products and ruminant meat, which includes primarily beef but also mutton and goat (Alexandratos and Bruinjsma 2012). Even though continuing improvements in feeding efficiency within each production system are assumed, the shift in production from developed to developing countries implies that overall feeding efficiencies would progress at a slower pace in the future than in the past. Shared socio-economic storylines are being developed under the auspices of the IPCC. Each storyline provides a brief narrative of the main characteristics of the future development path (see Kriegler *et al.* 2012):

- SSP1 is the sustainable world with strong development goals that include reducing fossil fuel dependency and rapid technological changes directed towards environmentally friendly processes including yield-enhancing technologies.
- SSP2 is the continuation of current trends with some effort to reach development goals and reduction in resource and energy intensity. On the demand side, investments in education are not sufficient to slow rapid population growth. In SSP2 there is only an intermediate success in addressing vulnerability to climate change.
- SSP3 is a fragmented world characterized by strongly growing population and important regional differences in wealth with pockets of wealth and regions of high poverty. Unmitigated emissions are high, low adaptive capacity and large number of people vulnerable to climate change. Impacts on ecosystems are severe.

Business-as-usual projections (SSP2) for the global food demand are consistent with the expert study by Alexandratos and Bruinjsma (2012). This storyline assumes a continuation of the intensification trend, although at a slower pace (4.6% increase in ruminant feed conversion efficiency per decade), as growth is expected to take place mainly in developing countries which have a lower feed efficiency. During this time period, the fraction of grassland herbage in the diets of domestic ruminants would decline at the same rate as before 3.4% per decade. Hence, the global herbage DM used by ruminants would be reduced by 0.5% per decade despite a small increase in grassland area (ca. 1.5% per decade). Compared to 2005, these trends translate into a 50 % rise in the livestock direct GHG emissions by 2050.

With the sustainable development projected under SSP1, a convergence towards healthy nutritional targets is assumed for food which reduces the global demand for red meat and to a lesser extent for dairy products. With this storyline, ruminant feeding efficiency would increase at the same rate (7 % per decade) as before, but the use of herbage in the diets would decline at an accelerated pace (-5.5% per decade) and, hence, the global herbage consumption by ruminants would be reduced by 40% by 2050 compared to 2005. The grassland area would not vary significantly and the livestock global direct GHG emissions would be stabilized in 2050 at the same level as in 2005. However, in some regions the under-utilisation of grasslands may lead to increased encroachment by woody vegetation with consequent reductions in GHG emissions (Elridge *et al.* 2011).

The SSP3 storyline depicts a fragmented world characterized by a fast growth in population and a slower global rise in GDP per capita and in animal products demand than in the business-as-usual scenario. With this storyline, ruminant feeding efficiency would increase at a much slower rate (0.75 % per decade) than in the past and the use of herbage in the diets would be almost stable (-0.6% per decade). The global direct livestock GHG emissions would increase by 30% and, moreover, GHG emissions from tropical deforestation would be fostered by the 20% rise in grassland area in 2050 compared to 2005.

Given their assumptions for the energy sector, these storylines lead to contrasted levels of global warming (*i.e.* +1.5, +2.0 and +2.5°C global warming by 2090-2099 compared to 1980-1999, assuming that SSPs 1, 2 and 3 match the 2.6, 4.5 and 6.0 W/m^2 global radiative forcing scenarios (see Rogelj *et al.* 2012). This implies that climate change would have moderate impacts on grasslands productivity under SSP1 and larger impacts under SSP2 and SSP3. Moreover, the livestock sector depends more on grassland resources under SSP2-3 than under SSP1.

We have tested with AgRipe the sensitivity of dairy and ruminant meat production to a climate change induced decline in grassland productivity by the end of the century. These tests can only be seen as preliminary, since they assume no climate change impacts on arable crops and on animal physiology. With SSP3, first results indicate that under climate change a 15% decline in global grassland productivity by 2050 would reduce global ruminant meat and milk production by ca. 8% compared to a control without climate change. Global ruminant livestock product-ion would be less affected (-5 %) under SSP2 and would only be marginally modified by climate change under SSP1.

Scenarios are neither predictions nor forecasts in a traditional sense; rather they are images of the future, or alternative futures that are meant to assist in climate change analysis (Nakicenovic, 2000). Among the many uncertaint-ies associated to such projections, we will now focus on the response of grasslands to climate change drivers.

Climate change impacts on grasslands

Climate change encompasses a range of major drivers (atmospheric CO_2 concentration, temperature and precipitation). Local changes in these drivers during the course of the century are less uncertain for atmospheric CO_2 than for seasonal temperatures and precipitations. Grassland response to these drivers is complex and is affected by interactions with water availability, nutrients, soil, vegetation and management conditions. Over the past 30 years, dozens of experiments have been undertaken to understand the impacts of climate change on grasslands. However, since most of these experiments are located in temperate and Mediterranean climatic areas, far less is known about climate change impacts on tropical grasslands and drylands.

Impacts of elevated CO_2 on photosynthesis and productivity

Elevated CO_2 concentrations stimulate photosynthesis, leading to increased plant productivity and modified water and nutrient cycles (*e.g.* Kimball *et al.* 2002; Nowak *et al.* 2004). Experiments under optimal conditions show that doubling the atmospheric CO_2 concentration increases leaf photosynthesis by 30-50 % in C_3-plant species and by 10–25% in C_4-species, despite a small but significant down-regulation of leaf photosynthesis by elevated atmospheric CO_2 concentrations at some sites (Ellsworth *et al.* 2004; Ainsworth and Long 2005). Photosynthesis in a sward canopy has also been found to increase by 30% (Casella and Soussana 1997; Aeschlimann *et al.* 2005).

The stimulatory effect of elevated atmospheric CO_2 concentrations on above-ground grassland ecosystem production reaches about 17% (Campbell *et al.* 2000; Ainsworth *et al.* 2003; Nowak *et al.* 2004), although responses for particular systems and seasonal conditions can vary widely. However, the long-term response to elevated atmospheric CO_2 concentrations may differ substantially from the short-term response. In the Swiss FACE experiment, the yield response of *Lolium perenne* to elevated atmospheric CO_2 concentration increased from 7 to 32% over a number of years under high applications of nitrogen (N) fertilizer. This increase was probably due to removing N limitation to plant growth through the application of N fertilizer (Luescher and Aeschlimann 2006). Therefore, the immediate response at the start of a CO_2 enrichment experiment is not an appropriate base on which to predict the impacts of the ongoing gradual increase in atmospheric CO_2 (Thornley and Cannell 2000). Moreover, the effects of elevated CO_2, as measured in experimental settings and subsequently implemented in models, may overestimate actual field and farm-level responses because of interactions with many limiting factors such as high temperatures, low nutrient concentrations, droughts, pests, weeds and air pollutants. We still do not know how much of the CO_2 fertilizing effect will remain under these complex conditions (Tubiello *et al.* 2007; Soussana *et al.* 2010).

Interactions of elevated CO_2 with water availability

Water availability plays a major role in the response of grasslands to climate change, with marked declines of productivity under increased water deficits, although there are differences in species response (Izaurralde *et al.* 2011). Increased productivity from increased water-use efficiency is the major response to elevated atmospheric CO_2 concentrations in C_3- or C_4- grassland species that are exposed frequently to water stress (Casella and Soussana 1997; Aranjuelo *et al.* 2005; Stokes and Ash 2006). Moreover, elevated atmospheric CO_2 concentrations can reduce depletion of soil moisture content in different natural and semi-natural temperate and Mediterranean grasslands (Morgan *et al.* 2004). These results support a view that elevated atmospheric CO_2 concentration reduces the sensitivity to low precipitation in grassland ecosystems (Volk *et al.* 2000; Morgan *et al.* 2004; Stokes and Ash 2006).

Interactions of elevated CO_2 with nutrients

Over a number of studies it has been found that plants grown in conditions of high nutrient supply respond more strongly to elevated atmospheric CO_2 concentrations than nutrient-stressed plants (Poorter 1998). FACE experiments confirm that high N soil contents increase the relative response to elevated atmospheric CO_2 concentrations (Nowak *et al.* 2004; Stokes and Ash 2006). With *L. perenne*, in the Swiss FACE experiment, increasing the N fertilizer application changed the grass dry-matter yield response to elevated CO_2 from being not significant to a significant yield increase of +17% (Schneider *et al.* 2004; Luescher and Aeschlimann 2006).

With a sub-optimal supply of N fertilizer, the nitrogen nutrition index of the grass sward, calculated as the ratio of the actual: critical leaf N concentrations, was significantly lowered under elevated atmospheric CO_2 concentrations (Soussana *et al.* 1996; Zanetti *et al.* 1997). This indicates a lower availability of inorganic N for the grass plants under elevated atmospheric CO_2 concentrations, which was also apparent from the significant declines in the annual N yield of the grass sward and in the nitrate leaching during winter (Soussana *et al.* 1996). At low N fertilization, this N limitation was also apparent over the 10 years of fumigation in the Swiss FACE experiment with monocultures of *L. perenne* (Daepp *et al.* 2000; Schneider *et al.* 2004).

Changes observed in the high N-fertilized swards of *L. perenne* may be summarized as decreasing N limitation (Luescher *et al.* 2006) in reference to the concept of progressive N limitation in natural systems (Luo *et al.* 2004). The CO_2-induced N limitation was alleviated in the high N-fertilizer treatment only by supplying a significant external input of N. These results confirm that N is a major limiting factor in the response of grasslands to elevated atmospheric CO_2 concentrations. When other nutrients are not strongly limiting, a decline in N availability may be prevented by an increase in biological N_2-fixation under elevated atmospheric CO_2 concentrations (Gifford 1994). Indeed, in fertile grasslands, legumes benefit more from elevated atmospheric CO_2 concentrations than non-fixing species (Hebeisen *et al.* 1997; Luescher *et al.* 1998) resulting in significant increases in symbiotic N_2 fixation (Soussana and Hartwig 1996; Zanetti *et al.* 1997). However, other nutrients, such as phosphorus, may act as the main limiting factor restricting growth and responses in yield in legumes to atmospheric CO_2 concentrations. This has been demonstrated both in calcareous grasslands (Stöcklin *et al.* 1998) and under controlled environmental conditions (Almeida *et al.* 2000).

Elevated CO_2-induced changes in soil C and N cycles

Plants grown under elevated atmospheric CO_2 concentrations generally increase the partitioning of photosynthates to roots which increases the capacity and/or activity of below-ground C sinks. In monocultures of *L. perenne* under elevated atmospheric CO_2 concentrations, the imbalance between a strongly increased C uptake in the shoot zone and a relatively reduced N uptake from the soil leads to an increased partitioning in growth to the root system (Soussana *et al.* 1996; Hebeisen *et al.* 1997; Suter *et al.* 2002). The ratio between leaf area index: total plant (root and shoot) biomass varied with the N supply, the atmospheric CO_2 concentration and the temperature (Calvet and Soussana 2001). As a result of these interactions, soils could cause spatial variation in CO_2 effects on above-ground Net Primary Productivity and other ecosystem attributes (Fay *et al.* 2012).

Plant species dynamics and diversity

Much of the world's grasslands are characterized by pastures that are botanically diverse. In a field experiment with varying levels of plant species diversity, the biomass accumulation in response to elevated levels of atmospheric CO_2 concentrations was greater in species rich than in species-poor assemblages (Reich *et al.* 2001). In some studies grassland communities grown in elevated CO_2 concentrations have displayed higher plant species diversity than controls under ambient CO_2 concentrations (Teyssonneyre *et al.* 2002a) but this was not confirmed in other studies (*e.g.* Zavaleta *et al.* 2003; Cantarel *et al.* 2013).

In mixtures containing grass, legume and nonlegume dicotyledonous species, the proportion of legumes was significantly higher at elevated atmospheric CO_2 concentrations (Luescher *et al.* 1996). This effect was also observed in diverse permanent plant communities in FACE and mini-FACE experiments (Teyssonneyre *et al.* 2002a; Harmens *et al.* 2004; Ross *et al.* 2004). In a mini-FACE experiment, elevated atmospheric CO_2 concentrations significantly increased the proportion of dicotyledonous species (forbs and legumes) and reduced that of the monocotyledons (grasses). Management differentiated this response as elevated atmospheric CO_2 concentrations increased the proportion of forbs when the plants were defoliated infrequently and of legumes when frequently defoliated (Teyssonneyre *et al.* 2002a).

In subsequent studies of between-species competition among three grasses, it was observed that grasses that capture relatively more light per unit leaf area in mixtures than their competitors become increasingly dominant under elevated atmospheric CO_2 concentrations (Teyssonneyre *et al.* 2002b). Moreover, a high N-use efficiency can confer a competitive advantage under elevated atmospheric CO_2 concentrations to mixed grasses (Soussana *et al.* 2005). Such experiments show that the diversity and botanical composition of temperate grasslands is likely to be affected by the current rise in atmospheric CO_2 concentrations, and that guidelines on grassland management will need to be adapted to a future world of high atmospheric CO_2 concentrations, warmer temperatures and altered seasonal precipitations (Hopkins and del Prado 2007).

Changes in species composition are also an important mechanism altering production of herbage and its value for grazing livestock in arid areas with changes in herbaceous species composition, in semi-arid rangelands with the invasion of woody shrubs (Elridge *et al.* 2011) and in warm humid climates with the invasion of C_4-species. Grassland weed distribution may also vary with climate change. For instance, the Chilean needle grass (*Nassella neesiana*), native to South America, has naturalised sporadically in parts of Western Europe, and more widely in Australia and New Zealand, where it has become a serious grassland weed. Under the future climate scenarios, a mean global reduction of 32% in the area of suitable climate is projected, with marked reductions in the native range and also in Africa, Asia, North America, and Australia. By contrast, projected expansions eastward in Europe and westward in New Zealand, result from increases in suitable area (Bourdôt *et al.* 2012).

Interactions between elevated CO_2 and climate change

Experiments with elevated atmospheric CO_2 concentrations and increases in temperature and precipitation have shown increased net primary production with strong multi-factor interactions, including changes in species distribution and litter composition (*e.g.* Shaw *et al.* 2002; Zavaleta *et al.* 2003; Henry *et al.* 2005). Nevertheless, even under elevated CO_2, the annual production of a semi-natural grassland in a French upland site was significantly reduced by four years exposure to climatic conditions corresponding to the A2 emission scenario for the 2070s (Cantarel *et al.* 2013).

The projected rise in climatic variability will tend to be associated with more extreme weather patterns (IPCC 2007a), leading to a potential for negative surprises that has not been fully explored, thus reducing the level of confidence in regional and global projections (Tubiello *et al.* 2007; Soussana *et al.* 2010). Combined with elevated atmospheric CO_2 concentrations, climate change is, therefore, likely to cause profound changes in the diversity, productivity and stability of grassland ecosystems. Results from a macrocosm experiment with the French Ecotron (www.ecotron.cnrs.fr) shows that elevated CO_2 can alleviate the impacts of a prolonged drought and heat event by inducing a compensatory regrowth of semi-natural grasslands after the end of the stress period (Picon-Cochard *et al.* in preparation).

Experimental manipulation combining heat and drought extremes shows large negative impacts on above-ground production, however with over-compensatory growth in the year following the extreme associated with plant community structure resilience (Zwicke *et al.* 2013 in press). With sown forage grasses (*Dactylis glomerata* and *Festuca arundinacea*), Mediterranean populations were more resilient than temperate populations to an extreme soil water deficit (Poirier *et al.* 2012), which underlines the potential for breeding better adapted plant material.

Repeated exposure of grasslands to summer droughts increased weed pressure by tap rooted forbs such as *Rumex* sp. (Gilgen *et al.* 2010). Moreover, increases in climatic extremes may suppress the dominance of C_3-species and promote C_4-species, including weeds, due to faster migration rates, greater production of seeds, better ability to colonize many habitats and rapid maturity (White *et al.* 2001).

A meta-analysis shows that physiological drought tolerance varies tenfold across grass species and is well distributed both climatically and phylogenetically, suggesting most native grasslands are likely to contain a high diversity of drought tolerance. Consequently, local species may help maintain ecosystem functioning in response to changing drought regimes without requiring long-distance migrations of grass species (Craine *et al.* 2013). Moreover, seedling survivorship of temperate grassland perennials is remarkably resistant to projected changes in rainfall, with a rainfall reduction of 40% reducing survivorship only by 10% (Perring and Hovenden 2012).

Forage quality

To meet the maintenance requirements of livestock for crude protein implies that the concentration of crude protein in herbage from pastures should be 70– 80 g/kg DM and to meet the requirements of the highest producing dairy cows it should be up to 240 g/kg DM. In conditions of very low soil N status, the reduction in crude protein concentrations of herbage under elevated atmospheric CO_2 concentrations may put a system into a sub-maintenance level for animal performance or require animals to be more selective in their grazing. C_4-grasses are a less nutritious food resource than C_3-grasses both in terms of a reduced crude protein concentration of herbage and in higher C:N ratios. Elevated atmospheric CO_2 concentrations will likely alter food quality to grazers both in terms of fine-scale (crude protein concentration and C:N ratio) and coarse-scale (C_3-species vs. C_4-species) changes (Ehleringer *et al.* 2002). However, when legume development is not restricted by adverse factors (such as low soil phosphorus content and low soil moisture content), an increase in the proportion of legumes in swards may compensate for the decline in the crude protein concentration of non-fixing plant species (Hartwig *et al.* 2000; Picon-Cochard *et al.* 2004). In North American cattle production systems, future increases in precipitation will probably not compensate for the declines in forage quality that accompany projected temperature increases, and cattle will experience greater nutritional stress in the future (Craine *et al.* 2010) likely requiring nutrient supplements for example via molasses-urea licks.

Projecting the impacts of climate change

Climate change impact analysis relies largely on down-scaling climate projections to develop regional climate scenarios for use in agricultural systems models. This process of climate down-scaling is complicated by differences in projections from greenhouse gas emission pathways and, in particular, the wide variation across global climate model outputs and across downscaling methods (Soussana *et al.* 2010). With pastures, projected impacts of climate change can be estimated from projections of mechanistic models that simulate the interactions between climate, soil properties, pasture species and grazing animals although many challenges remain in providing robust simulations at landscape level especially in tropical regions. In order to assess uncertainties arising from the variability across models, an ensemble of downscaled climate models is needed to reflect the local distribution of key climatic variables like rainfall (Challinor *et al.* 2007; Graux *et al.* 2013, Moore and Ghahramani 2013).

Several modeling studies have shown compensatory effects of elevated CO_2 and climate change at temperate sites (Parton *et al.* 1995; Riedo *et al.* 1999). The combination of these two factors enhanced forage production and soil organic matter, however, with considerable variation across sites, management and local climatic conditions (Riedo *et al.* 2000, 2001; Holden and Brereton 2002; Graux *et al.* 2013a,b). In addition, warming extended the growing season (Hunt *et al.* 1991) and shortened the plant phenology (Juin *et al.* 2004). These impacts were anticipated to affect grassland and livestock management (Holden and Brereton 2002; Juin *et al.* 2004) and profitability (Parsons *et al.* 2001). With grass based dairy systems, simulations under the A1B scenario with an ensemble of downscaled GCMs show by the end of the century increases in potential dairy production in Ireland and France, however with increasing risks of summer-autumn forage production failures at French sites (Fitzgerald *et al.* 2010; Graux *et al.* 2013) . In continental Europe, grass based dairy systems could suffer from rising water deficits and forage yield variability (Trnka *et al.* 2009).

Responses of sheep and cattle grazing systems to climate and CO_2 changes can vary markedly across environments. For example, Moore and Ghahramani (2013) show that climate changes reduce productivity and profit to a greater degree in dry sites in Australia than in wetter sites where there may be some chance of increased productivity and profit similar to that found by others (*e.g.* Cullen *et al.* 2012). Impact can also vary with pasture type: Bell *et al.* (2012) simulated that sheep grazing systems at four sites in southern Australia show lower pasture intakes and lamb live weights at weaning in future climates with C_3 temperate pasture species. With warming, a site with a C_4-based pasture system became significantly more productive and with a lower GHG emissions intensity.

A probabilistic risk analysis can be developed, by defining risk as the product of hazard probability (*e.g.* the probability of drought occurrence) and the response to hazard (Van Oijen *et al.* 2013). With this approach, a significant increase in exposure to summer drought risk was evidenced for French grasslands (Graux *et al.* 2013). Simulated future conditions show an increased inter-annual and seasonal variability of grassland production. Dairy production at grazing in summer is estimated to drop down below one-third of the current median value in four out of 30 years for 2070–2099, whereas similar shortfalls were not observed with the baseline climate (Graux *et al.* 2013). A detailed analysis of risks under the A1B emission scenario further shows that European grasslands could shift from a carbon sink (Schulze *et al.* 2009) to a carbon source for the atmosphere, that may reach 270 TgC per year towards the end of the century (Lardy *et al.* in preparation).

Regional hot-spots for grasslands and livestock vulnerability

Regional hot-spots to climate change can be characterized through the combination of high exposure to climate change, high sensitivity (often because of other stressors such as land degradation) and low adaptive capacity. Below, we discuss the main factors that could be used to define regional climate change hot-spots for grasslands.

Exposure to climate change

Grasslands are the ecosystems that respond most rapidly to precipitation variability. Increased aridity and persistent droughts are projected in the twenty-first century for most of Africa, southern Europe and the Middle East, most of the Americas, Australia and South East Asia (Field *et al.* 2012). A number of these regions have a large fraction of their land use covered by grasslands and rangelands (Fig. 1).

Within each region, however, there are differences in climatic trends which can also be seen through historical analyses. In Brazil, a recent study (Carvalho *et al.* 2013), analyzing historical data from 1940 to 2011, has shown a trend for increased occurrence of dry spells in the Midwest (the main cattle production region), but not in the South or Southeast regions. In African Sahel, average regional rainfall since more than a century shows an increase of rainfall since 1990 following a period of important surpluses from 1950 to 1970 and of intense deficit and frequent drought crisis from 1970 to 1985 occurring when two consecutive high annual deficits occur. Nowadays, despite an increase of average rainfall, we notice a high variability of annual rainfall average, close to what was reported in early XXth century.

During the early twenty-first century droughts, satellite based studies for the USA and Australia indicate that capacities and sensitivities of grassland and rangeland production were maintained through prolonged heat waves and droughts by increases of ecosystem water use efficiency during the driest years and resilience during wet years. During the driest years, the high-productivity sites became water limited to a greater extent resulting in higher WUEe similar to that encountered in less productive, more arid ecosystems (Ponce Campos *et al.* 2013). Nevertheless, with continuing warm drought, significant drought-induced mortality reduces the water use efficiency and a loss of resilience appears (Ponce Campos *et al.* 2013).

Dryland degradation and its sensitivity to climate change

Degradation of drylands typically shows one of the following general patterns, mainly depending on the precipitation received: either vegetation composition changes, leading to shrub encroachment or vegetation cover in general which is drastically reduced and the fraction of bare ground is increased with temporarily dominating annual grasses or forbs (Asner *et al.* 2004; Miehe *et al.* 2010; Lohmann *et al.* 2012). Proliferation of woody plant species in semi-arid grasslands and savannas in recent history has been widely reported around the world. The causes for this shift in vegetation are controversial and include changes in livestock grazing, fire, climate and atmospheric CO_2 concentrations (Hibbard *et al.* 2001).

Projected increases in climate variability and increases in the length of the dry summer period is likely to impact negatively on ground cover in Mediterranean climates, increasing soil erosion risks (Crimp *et al.* 2010). Moore and

Figure 1. Drought hot spots in global grazing lands by 2080-2100. The colour scale indicates the percentage cover by grazing land in each grid cell. Circled in red, are areas with a significant increased number of consecutive dry days in 2080-2100 compared to 1980-2000 (Field *et al.* 2012).

Ghahramani (2013) and Ghahramani and Moore (2013) undertook simulation analyses which adjusted stocking rates to maintain the frequency of days with ground cover <0.7 below location-specific thresholds so as to keep erosion risk at acceptable levels. This resulted in significantly greater reductions in productivity and profit than would have been assessed on annual average NPP alone. The sensitivity of systems to these types of non-linear responses requires more study.

There could be competing drivers for shrub encroachment into grasslands. On the one hand, increased mean temperatures may reduce shrub encroachment in some regions (Lohmann *et al.* 2012) and if this occurs, the reduced competition from woody species in turn could increase the success of alternative restoration measures such as the (re-)introduction of desired grass species. In contrast, recent experimental and observational evidence suggests that factors such as increased rainfall intensity (Kulmatiski and Beard 2013), CO_2 and fire (Eldridge *et al.* 2012) that may occur with climate changes may increase woody encroachment, with the opposite effects on some restoration.

Shifts in biomes

Climate change may result in potential vegetation shifts. In the forest-savannah boundary of the Brazilian Amazon, GCMs and land surface models depict a climate-driven substitution of large portions of Amazonian forest by grass-dominated ecosystems (Senna 2009; Silvério *et al.* 2013). Amazonia is likely to suffer a general reduction in rainfall and an increase in surface temperature (Oyama and Nobre 2003; Cox *et al.* 2004; Huntingford *et al.* 2004; Senna *et al.* 2009), partly due to projected El Niño-like sea surface temperature warming patterns (Cox *et al.* 2004) and deforestation positive feedbacks on externally forced climate change (Cox *et al.* 2004; Senna *et al.* 2009). In such conditions, drought events associated with more intense and frequent fires may facilitate the spread of invasive C_4 grasses over the Amazon (Silvério *et al.* 2013).

In Western Africa, model results show a potential 'greening' trend by 2050, where the bioclimatic envelope of grassland is projected to expand into the desert by an area of 2 million km^2 (Heubes *et al.* 2011). However, there is a large uncertainty which results from the variability in projection by different climate (Global Circulation Models, GCM) models and from the human impact of livestock management. In China, an eastward shift and an expansion of grasslands is projected by biome models forced by GCMs under elevated CO_2 (Ni, 2011). In Northern Europe, global warming may not necessarily expand the growing zone for temperate grasses to the north and east of the study area by 2050, since projections show continued risks of frost damage to perennial ryegrass during winter, which would limit the improvement of overwintering conditions (Höglind *et al.* 2013).

Adaptive capacity and vulnerability

Enhancing the ability of individuals to respond to a changing climate will occur through building adaptive capacity. In Australia, a national composite index of generic adaptive capacity of rural households expresses adaptive capacity as an emergent property of the diverse forms of human, social, natural, physical and financial capital from which livelihoods are derived (Nelson *et al.* 2010a,b). The same approach has also been implemented at regional (Crimp *et al.* 2010) and farm scales (Brown *et al.* 2012) and over time (Crimp *et al.* 2010). These types of studies allow for more effective policy implementation to build adaptive capacity. They also show that financial, social and human capital and the substitutability between these are the main determinants of vulnerability rather than environmental aspects such as climate. In contrast, other studies have indicated that the degree of vulnerability to climate change is particularly sensitive to the effects of precipitation on NPP (Hulme *et al.* 2001; Olesen 2002; FAO 2008a, b). But as noted above vulnerability is also a function of socio-economic condition: the degree of exposure to climate (related to the degree of economic dependence on agriculture) and the capacity to adapt to change in climate (Vincent 2004; Thornton *et al.* 2006).

In areas with expected declines in forage yields, increased occurrence of extreme events (direct effects of drought, heat stress, flooding, etc. as well as indirect effects such as pest outbreaks) coupled with low adaptive capacity, can make smallholder subsistence pastoralists and farmers highly vulnerable to climate change (Easterling *et al.* 2007). Low-latitude, grazing land-dominated countries, while contributing the least to greenhouse gas emissions, may be the hardest hit, and the poor could suffer the greatest repercussions (FAO 2008c). Despite long-established socio-economic systems to deal with persistent inter-annual variation in precipitation (Thornton *et al.* 2006), such countries are uniquely vulnerable because they suffer from high temperatures, less predictable rainfall, and substantial environmental stress (Oba *et al.* 2001; FAO 2008c; Sheffield and Wood 2008).

Small-holders in particular often have the lowest capacity to adapt and are likely to be among the most vulnerable because social, economic, climatic risks are high in their environment and combined with low opportunities to adapt as a consequence of low investment of states in local development and infrastructures, inadequate institute-ions, low access to information and unsecure rights on land and natural resources (Easterling *et al.* 2007; Ickowicz *et al.* 2012). However, other authors note that people in some disadvantaged conditions can be highly innovative and can have more adaptive capacity than more affluent neighbours (Morton *et al.* 2007; Coulthard 2008)

Increased vulnerability under climate change would result from decreased forage yields, decreased water availability, increased incidence of droughts and floods and extreme events (Tubiello *et al.* 2007), significant extinction of plant and animal species (World Bank 2007) and increased migration and civil conflict (Schmidhuber and Tubiello 2007; FAO 2008c; IMF 2008).

The search for practical solutions: how to adapt, how to mitigate?

To date, the assessment of synergies and trade-offs between mitigation and adaptation options in animal agriculture has been limited (*e.g.* Smith and Olesen 2010).

Towards climate smart grasslands

Climate smart agriculture has been defined as agriculture that sustainably increases productivity and resilience (adaptation), reduces GHGs (mitigation), and enhances food security and development (FAO 2010). To develop climate smart grassland systems, a sustainable intensification, that would reduce productivity gaps and increase the efficiency of livestock production, especially in developing countries, is required to enhance food security and contribute to mitigate climate change by stopping deforestation and the expansion of grasslands into savannahs.

Recent reports of the lifecycle of dairy and meat products to the farm gate and beyond show large differences in GHG emissions per unit animal product across regions and across systems. Intensive systems, including grassland based temperate dairy and meat production, have much lower GHG emissions per unit production than extensive pastoral systems (FAO 2010 2013). Nevertheless, because of their low production levels extensive systems contribute in a limited way to the overall emissions of the sector and may thus not represent a priority area for mitigation interventions, also in view of their crucial contribution to food security in harsh environments.

On a global scale, intensifying grassland production will be required if we are to increase meat and milk production from ruminants systems, while minimizing competition for arable land between food and feed and preserving biodiversity and ecosystem services (Thornton 2010). More productive and climate resilient grassland systems may also lead to beneficial side effects in terms of carbon sequestration and reduction of GHG emissions per unit animal production. However, win-win options are currently limited by gaps in our understanding, as well as by a number of economical and institutional barriers.

Resistance, resilience and transformation strategies for grassland adaptation

Resistance strategies (or incremental adaptation) seek to maintain the *status quo* over the near term through management actions that resist climate change disturbance (Easterling 2009; Walthall *et al.* 2013). Resistance strategies, will likely increase in cost and difficulty over time, and may ultimately fail as climate change effects intensify. Resilience strategies (or more systemic adaptation) are typically proactive actions that increase the adaptive capacity so as to return to a healthy condition after a climate disturbance with minimal management intervention. Transformation strategies increase adaptive capacity by facilitating transition to a new system with a different structure and function that is better suited to sustained production under rapidly changing climate conditions (Park *et al.* 2012, Rickards and Howden 2012).

Resistance strategies include re-sowing a pasture after it has failed because of a drought, overgrazing a degraded pasture in order to cope with the after-effects of a climate extreme, frequently burning a degraded and encroached rangeland to restore herbage growth. Such resistance strategies are widespread currently, and they may be useful in the short term to cope with climatic variability. However, they are likely to fail in regions exposed in the future to *e.g.* prolonged droughts and heat waves. Such resistance strategies may in fact lead to maladaptation, by reducing the adaptive capacity of the grassland ecosystem and releasing CO_2 to the atmosphere through soil degradation.

Resilience strategies may be implemented by considering grasslands as a dynamic mosaic, formed by spatially heterogeneous resources which vary throughout time. Strategic inter-annual planning of the use of this resource by the herd and in season tactical adjustments taking into accounts differences between grassland fields in terms of vegetation and making use of animal mobility and animal reserves may improve the adaptive capacity of the managed grassland. Changes in livestock species (*e.g.* using zebu instead of beef cattle) and mixed grazing may also provide increased resilience. With perennial vegetation, the grazing process can be improved by rotating animals while keeping a high instantaneous stocking density, often by herding or moving electrical fences which may be powered by photovoltaic in remote areas. In this way, a larger share of the available forage is used and grass growth can be maximized by limiting digestible carbon losses through plant respiration and senescence. Such strategies are already in place in some regions, but their future development may require advanced technologies such as seasonal forecasting of weather conditions and pastures geo-monitoring. Gharahmani and Moore (2013) show the benefits of using multiple adaptations to address climate changes can substantially outweigh those arising from single adaptations. Nevertheless, particularly at the dry margins of current grazing, these multiple adaptations were not enough to offset negative impacts and in such circumstances, even more substantial adaptation (called transformational adaptation) may be considered.

Transformation strategies may move livestock farmers out of the grassland sector since they may need to rely to a greater extent on other feed sources (*e.g.* conserved forage, crop residues and by-products). However, depending on the local context, adaptation of grassland systems may also lead to other options which are detailed below (changes in pasture species, irrigation, pasture restoration, crop-pasture integration, agro-forestry, etc…), with different options available when contrasting tropical, temperate and Mediterranean grasslands.

Temperate and Mediterranean grasslands

Generally speaking an environmentally sustainable intensification of grassland based animal production could be obtained by increasing net primary productivity and herbage quality, while raising animal protein conversion efficiencies (through breeding, nutrition and improved health), replacing inorganic N fertilizer inputs by biological N fixation and recycling efficiently the organic N from animal excreta. This would in effect increase the carbon flowing towards both animal products and soils, while re-coupling the C and N cycles and reducing losses to the environment.

<u>A moderate intensification of pastures</u>. Temperate grasslands have often been intensified by combinations of: (1) an increased primary production through an improvement of the N-P-K status of vegetation; (2) an increased stocking

density for converting more efficiently herbage production into animal products; and (3) sowing, or over-sowing, of improved grass and legume species. Intensification has three contrasting effects for the carbon cycle of grasslands: first, an increase in the net primary productivity; second, a decline in the amounts of organic carbon returned to the soil (Soussana *et al.* 2007); third, a possible decline in the turnover of soil organic matter when nutrients are in ample supply for soil microbes (reduced priming effect, Fontaine *et al.* 2007, 2011). Depending on the balance of these effects, the impacts on the soil carbon balance may vary. Grassland intensification also leads to increased emissions of N_2O from fertilizers and biological N fixation, and to increased methane emissions from enteric fermentation. In comparison to an unfertilized control pasture, doubling the animal stocking density and supplying mineral N fertilizers led to increased net GHG emissions per unit area at an upland permanent pasture site in France (Allard *et al.* 2007). However, during dry years, the moderately intensive grassland was more resilient in terms of carbon storage, emitted less GHGs, and provided increased cattle live-weight gains (Klumpp *et al.* 2011). Therefore, a moderate intensification of permanent pastures could provide an interesting combination of mitigation and adaptation.

In contrast, some grasslands have been over-intensified with excess N fertilizer applications, leading to large direct (N_2O) and indirect (NH_3, NO_3^-) GHG emissions, to water and air pollution and to relatively low soil organic carbon stocks (Soussana *et al.* 2004). Given the projected rise in fossil energy and fertilizer prices, such management systems are likely to become increasingly costly. Moreover, they may become inefficient under an increased climatic variability since applying fertilizers before drought spells and heavy precipitation would only add to the losses to the environment. Strategic and tactical optimization of N (and P) fertilization will therefore be increasingly required in grassland management to increase efficiency, mitigate GHG emissions and adapt grass growth to a variable climatic potential. In the same way, by avoiding the frequent ploughing of sown grass leys (*i.e.* by increasing the duration of the leys) a moderate degree of intensification can be attained with benefits in terms of increased soil organic C stocks (Soussana *et al.* 2004).

<u>Pasture irrigation</u>. Pasture irrigation is confined to a small number of regions worldwide, mostly in developed countries with temperate and Mediterranean climate, where water infrastructure are in place an pasture areas relatively accessible. Its future expansion will be challenged by the increased scarcity of water resources, by the competition with food crops and by the costs of the irrigation equipment. Therefore, although irrigation is a prominent option for climate change adaptation of agriculture, it is unlikely that grassland irrigation can be developed on a large scale to meet the demands of forage by ruminant livestock. Moreover, irrigation is demanding in terms of energy use and adds to the GHG emissions of livestock systems. Nevertheless, the planned development in some countries of solar desalinization plants may open a potential for increased irrigation of high quality forage production (*e.g.* for local milk production).

<u>Using sown grass-legume mixtures.</u> Managing grasslands with less mineral N fertilizers and with an increased reliance on biological N fixation is a desirable objective in order to reduce the costs of inputs, to avoid greenhouse gas emissions caused by the industrial synthesis and by the transport of mineral N fertilizers and to increase the digestibility and protein content of the herbage (Frame and Newbould 1986).

Legumes have a distinct competitive advantage in N-limited systems, but where mineral-N is abundant, N_2 fixation is energetically costly and N_2 fixers tend to be competitively excluded by non-fixing species (Faurie *et al.* 1996; Soussana and Tallec 2010). In a pan-European experiment involving 17 countries, grass-clover mixtures, containing two species of grasses and two species of legumes frequently had a higher yield than the highest of the monoculture plots (Finn *et al.* 2013). Grass-legume mixtures with proportionately *ca.* 0.30 to 0.50 of legume in pastures seem to be an optimal system: they yield high amounts of N from symbiosis, generate high net primary production, produce forages of high nutritive value, which generates high voluntary intakes and livestock performance and, at the same time, they prevent the risk of N losses to the environment and they may store more carbon in the soil than fertilized grass monocultures (Luescher *et al.* 2012; Soussana *et al.* 2004). Moreover, temperate legumes may offer an option for adapting to higher atmospheric CO_2 concentrations and to climate change since their growth and their relative abundance in mixtures is increased by elevated CO_2 and at warm temperatures (Soussana and Hartwig 1996; Teyssonneyre *et al.* 2002). The big challenge for legume-based grassland-husbandry systems, however, will be to maintain the proportion of legume (Luescher *et al.* 2012), which declined in the swards of the pan-European experiment in its third and last year (Finn *et al*. 2013). This decline was, however, largely prevented in more diverse grass-legume mixtures (with up to 8 species) (Suter *et al*. 2010). Ongoing experiments are testing at a range of European sites the drought tolerance of grass-legume mixtures, since increased drought frequency could prevent the development of legume based grasslands.

<u>Adapting the plant material and using plant functional diversity</u>. The selection of ecotypes that are adapted to more extreme climatic conditions could be an option for maintaining future ecosystem functioning in temperate grasslands, as was indicated by the clear differences between ecotypes in a warming and extreme drought experiment with temperate grass species (Beierkuhnlein *et al.* 2011). With sown forage grasses, Mediterranean populations were more resilient than temperate populations to soil water deficit (Poirier *et al.* 2012) and could therefore be used to breed better adapted plant material, despite being less productive in wet years than temperate origins. Grass-legume mixtures will need to be adapted to the increased occurrence of droughts through targeted breeding programs also aiming at developing complementarity effects between species. Other options include the use of summer dormancy grasses (Volaire *et al.* 2009) and the breeding of deep-rooted (*e.g.* tap roots) legumes and forbs and of rhizomatous grasses, since those life forms tend to better resist drought. The increased drought tolerance conferred by endophytes to temperate grasses (such as tall fescue)

could also be used, assuming that the negative impact of the endophyte on animal performance can be avoided.

However, under a strong warming scenario, it cannot be precluded that much larger changes in grassland systems will be required in regions which are currently temperate and are dominated by perennial C_3 grasses. For instance, shifting in moist areas to C_4 forage grasses and shifting in dry areas to annual legumes could be considered as options to explore by the end of the century. Preserving plant genetic resources will help keeping options open for the future. Finally, preserving species diversity in grasslands also enhances resilience to disturbance risks and would preserve the multifunctionality of grasslands in drought prone areas (Maestre *et al.* 2012).

In regions with intermittent drought conditions, perennial woody species typically have more robust and deep root systems that can keep producing forage when grass and forb species have stopped providing significant feed, thus providing a potential buffer against increased future climatic variability. Recent research has shown that some of these woody perennials have anti-methanogenic properties (Durmic *et al.* 2010), thus potentially providing both adaptation and mitigation option if effectively integrated into grazing systems. Similarly, in high rainfall grazing zones, high sugar content grasses with strong drought resistance and good digestibility might become more important as climate changes further.

Tropical grasslands

<u>Pasture intensification</u>. Mitigation practices in ruminant systems are generally associated with productivity gains, especially where productivity is currently low. At the animal level, improvements of feed digestibility, feed balancing and health conditions lead to greater yields and reduced emissions, resulting in reduced emission intensity. At the herd level, emission reductions can be achieved by increasing the relative importance of productive animal cohorts (milked and fattened animals) in the herd. Lastly, adopting better grazing management practices to sequestrateing carbon in soils often results in higher grass production (FAO 2013).

Tropical grasslands can substantially increase soil carbon, even above natural vegetation levels and sown mixtures with legumes seem to further improve soil carbon accumulation rates (Cerri *et al.* 2004; Neely *et al.* 2009). The substitution of native pasture species by African species, particularly *Brachiaria* (*Urocloa*) spp., *Panicum* spp. and *Cynodon*, has happened similarly in other tropical countries of Latin America, Asia, Australia and in the Southern United States and is likely to increase soil carbon storage (Fisher *et al.* 1994). *Brachiaria* and *Cynodon* species tolerate acid and low fertility soils of the tropics but their level of productivity is highly dependent on soil nitrogen content. For high pasture productivity, liming (also a source of GHG emissions), P and K fertilizers are required. In most of Africa and Latin America, tropical pastures receive low fertilizer inputs. Although the literature point to cases of successful mixtures between C_4 grasses and legumes (C_3), high levels of adoption were not obtained in the commercial production systems, particularly because of management and persistence issues.

Therefore, increasing pasture productivity to accumulate soil carbon may have to rely, in the short-term at least, either on higher direct nitrogen fertilization of grasslands or on larger adoption of crop-livestock integrated systems. By using deep rooted C_4 grass species (*e.g. Brachiaria*) a relatively low sensitivity to seasonal droughts has been achieved in a number of trials in Brazil and other countries of Latin America. However, expanding *Brachiaria* grasslands in savannah areas implies clearing the trees and plowing up the soils and this has large carbon costs and may reduce drastically plant species diversity. Ranching intensification would therefore need to focus on areas which have already lost their native vegetation.

<u>Pasture restoration</u>. The low fertility of tropical soils coupled with low fertilizer application results in declining productivity of grasslands over-time, which, without careful stocking rate adjustments, may also end up in overgrazing. Therefore, large areas of grasslands are found in some stage of degradation with consequent soil carbon losses. For instance, in Brazil, analysis of municipality aggregated data, shows that there is over 25 million ha of grasslands with stocking rates lower than 0.62 animal units per ha because of pasture degradation occurring within moderately intensive production systems. There is a large potential for annual C sequestration following cessation of overgrazing and implementation of moderate grazing intensities (Conant *et al.* 2002). Improving pasture and grazing land productivity through pasture restoration is also critical to reduce pressures on land and to provide increased resilience to climatic extremes. There are a number of options available, such as:

- Supplementing grass (*e.g.* with conserved roughage, grains and oilseed meals) during the dry and cold seasons in order to avoid overgrazing, restore pasture productivity and increase meat and milk production,
- Improving the animal breeds and investing in animal health (*e.g.* vaccination) in order to increase the feed conversion efficiency and, hence, waste less forage;
- Plant improved grasses and legumes, and fertilize them to produce larger and more digestible forages.

Enhancing pasture management, crop-livestock integration, supplemental feeding and improved health allow for changes in the actual to potential production ratio. Increasing productivity would also generate increased economic performance of the systems while avoiding the expansion of pastures into forested areas (Gouvello *et al.* 2011; Cohn *et al.* 2011; Strassburg *et al.* 2012).

<u>Silvo-pastoral systems</u>. Agroforestry arrangements that combine fodder plants, such as grasses and leguminous herbs, with shrubs and trees used for animal nutrition and other purposes such as fencing and sun protection for animals. They include scattered trees in pastureland, live fences, tree based fodder banks and cut and carry systems. Restoration of extensive silvopastoral systems in African arid and semi-arid areas that have been subject to high mortality of trees and shrubs as a consequence of droughts crisis mainly (Miehe *et al.* 2010; Diouf *et al.* 2005) is an option to regenerate rangeland productivity once stoking density is well managed. In these systems, trees and shrubs have been described to enhance carbon sequestration in

soils through root systems and are also beneficial as bird habitat and shade providers (Akpo *et al.* 1995). Moreover, they increase the quality of diet for ruminants with a contribution up to 50 or 80% of DM intake for cattle and small ruminant respectively with protein content at least four times that of grasses in dry season (Guerin *et al.* 1988; Ickowicz and Mbaye 2002).

Intensive silvopastoral systems can be directly grazed by livestock and include fodder shrubs (*e.g. Leucaena* sp.) and productive pasture species. Such systems can protect biodiversity and can be combined at landscape scale with connectivity corridors and protected areas. Silvopastoral systems that integrate eucalyptus, crop and pastures are becoming more common in the Brazilian savannah and have also been associated with increased soil fertility through the continuous supply of organic matter and better land management practices (*e.g.* avoiding erosion) (Vilela, 2001; Ribeiro *et al.* 2007; Tonucci *et al.* 2011). They provide a large carbon sequestration potential and are likely to be more resilient to heat waves and to droughts, and to provide shading to livestock. The area to produce 1 ton of meat would move from 14.8 ha to 5.5 ha and 1.2 ha, respectively, in the dry region of Colombia for extensive pastures, improved pastures and intensive silvopastoral systems, respectively (*J Chara, Centre for Research on Sustainable Systems for Agricultural Production, Cali Colombia, Pers com*). However, many barriers still exist to the adoption of silvopastoral practices. High initial costs, slow return on investment, and an overall unawareness of the benefits suggest that efforts need to be done by the scientific community and stakeholders towards building capacity and financing.

Socio-economics and policy dimensions of mitigation and adaptation

The balance and urgency to adapt or mitigate differs across different parts of the world. Understanding when and where these actions can be made synergistic and how they can support other policy objectives such as poverty alleviation, food security or ecosystem goods and services is a major question.

Some livestock mitigation measures may be costly to implement relative to the costs of reducing equivalent volumes of emissions in other sectors of the economy - *e.g.* in transportation, energy or industry (Smith *et al.* 2008). Economic mitigation potential tends to be defined using marginal abatement cost curve (MACC) analysis. MACCs are useful tools for identifying the most cost-effective mitigation measures. On a global scale, improved grassland management and reduced conversion of pastureland were estimated to have a significant mitigation potential (ca. 3 $GtCO_2e$ per year by 2030) at a very low cost (McKinsey 2010). In UK, manure management is a prominent mitigation option which would have a negative cost (Moran *et al.* 2010). In France, grassland management would provide mitigation at a negative cost (Pellerin *et al.* 2013). The link between productivity gains and emission intensity reductions explains why marginal abatement cost analyses have often found a negative cost associated with mitigation practices (McKinsey 2010). Upfront investment costs, access to knowledge and higher risks associated with intensified production practices may however be objective constraints to the adoption of practices that increase productivity (Moran *et al.* 2010). Further research is required to identify and develop new techniques, but also to combine available techniques into packages that effectively and durably amplify their effect in specific production systems and environments.

The costing of adaptation measures is an under-researched area for grasslands and livestock. The benefit accruing to an adaptation cost is the value of the damage avoided which means a central damage scenario is needed and, where uncertainty exists, a range, plus a monetary valuation of the damages. The former challenge is complicated by uncertainty both in terms of the impacts and of the responses of farmers and land managers. With grassland systems, adaptation effectiveness is moreover confounded by the biophysical complexity of different farming systems.

These constraints call for specific policies that can provide the right incentives for technology transfer and emission reduction. Extension, research and development, financial incentives, prescriptive regulations, market instruments and advocacy are all instruments that can be mobilized by governments and private sector organizations to foster innovation. Substantial additional research is however needed to assess the costs and benefits of mitigation and adaptation practices in greater detail, before designing incentive frameworks. Policy instruments and research programs are unlikely to be put in place in the absence of any international and cross-sectoral commitments to curve anthropogenic GHG emissions and of national strategies to implement such commitments. Nationally Appropriate Mitigation Actions (NAMAs) are promising instruments to guide and support mitigation intervention in grassland systems. To date, only six countries have included livestock as part of their mitigation strategy (Brazil, Chad, Jordan, Madagascar, Mongolia and Swaziland), and Brazil only submitted a quantitative target; committing itself to an ambitious 83-104 Mt CO_2-eq reduction through grassland restoration and conservation, and 18-22 Mt CO_2-eq from improved livestock management, including efficiency, in 2020[1]. A number of additional countries are however now also engaging in this process. To be fully effective, and given the complexity of the livestock sector, the design and implementation of cost-effective and equitable mitigation strategies and policies will benefit greatly from concerted action by all stakeholder groups engaged in supply chains (including producers, industry associations, academia, the public sector and intergovernmental organizations).

Concluding remarks

Research on the interactions between climate change and grasslands has been rapidly expanding in recent years, but much remains to be done in order to improve our ability to project future changes and to offer practical solutions. The metrics of adaptation and mitigation needs to be agreed

1 http://unfccc.int/files/meetings/cop_15/copenhagen_accord/application/pdf/brazilcphaccord_app2.pdf; http://www.brasil.gov.br/copenglish/overview/what-brazil-is-doing/domestic-goals/print

internationally and its compatibility with food security assessed, as incentive frameworks will require a firm basis for the calculation of the costs and benefits of mitigation and adaptation practices. While we now benefit from a large number of local observations, we still lack long-term experiments testing grassland mitigation options and their impacts on GHG emissions and removals and free-air grassland manipulation experiments combining warming and altered precipitations. Such data are essential to improve models and their ability to simulate a range of adaptation and mitigation options. Increased international collaboration in this area is a priority to foster science and innovation.

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