Sustainability, biodiversity and environmental issues A global perspective for livestock production

D.L. Michalk

Director
Orange Agricultural Institute (NSW Agriculture)
Charles Sturt University,
Graham Centre for Agricultural Innovation, AUSTRALIA
E-mail :dm.hainan@gmail.com

ABSTRACT

To meet world food demand through the 21st century, agricultural production needs to increase, but this needs to be done sustainably through increasing *efficiency*, optimising *sufficiency* and achieving *consistency*, such that resource use is optimised, waste reduced and environmental benefits gained. These strategies need to be developed against changing food patterns, especially a decline in per capita consumption of cereals and an increase in meat consumption as household incomes increase. Grasslands are collectively the larger group of land-based ecosystems on the planet. Their values are not always recognised, often being seen as 'reserves' for exploitation for urban expansion, for cropping or some other use – conversion to these other uses is continuing at a high rate. Their exploitation often leads to greater environmental and socio-economic problems. Over-grazing is typically the main influence on grassland productivity, reflecting the pressures from excessive human populations and a demand for food. Some 20% of the world's grasslands are in a severely degraded state; others have suffered shifts to less-desirable species with consequently reduced productivity. Estimates of productivity change all show a declined over recent decades, yet animal numbers continue to increase, particularly in the developing world. Restoring productivity to achieve both livestock production and environmental benefits are desirable but not widely practiced in developing countries. Biodiversity and greenhouse gas production have been particular concerns, but the methods used to monitor them have not always suited an agricultural context – solutions are proposed. The large differences in livestock production efficiencies between the developed and developing world highlight how existing knowledge can be used to achieve major improvements that in turn would show major benefits for the world's livestock industries.

Keywords: livestock productivity, efficiency, pathways, over-grazing

Introduction

The major imperative of the 21st century is to meet growing demands for agricultural output and food security while preserving essential ecosystem processes on which both long-term agricultural production and human well-being depend (Johnson *et al.* 2014). By 2050, the agricultural sector has the huge challenge to produce 60% more than the current food, feed and fibre supply (8.5 billion t/y) to sustain a global population forecast to be 9.3 billion people (FAO, 2014a). Although agriculture is the largest land user on the planet, it will not be possible to achieve this level of production and, at the same time safeguard the planet's natural resources for future generations, without fundamental changes to our agriculture production and food processing systems.

Food output can be increased through intensification (*i.e.* higher yields per hectare) and extensification (*i.e.*using more hectares). In the past, technological innovation and improvements such as high-yielding plant varieties, irrigation and high levels of chemical inputs increased global agricultural production more than threefold in 50 years with only 12% growth in the farmed area (FAO, 2014a). This Green Revolution which increased cropyields not only allowed farmers to improve food availability for poor consumers at affordable prices but, by saving millions of hectares of grasslands and forests from conversion to agricultural land, it saved an unquantifiable quantity of ecosystem services and avoided the release of an estimated 590 billion tonnes of carbon dioxide (CO_2) into the atmosphere (Burney *et al.*, 2010).

Recent forecasts estimate that intensification will account for 80% of the future increase in global agricultural production with extensification accounting for 20% (Alexandratos and Bruinsma, 2012). In biophysical terms, closing 'yield gaps' on under-performing lands by further increasing cropping efficiency, shifting dietary preferences and reducing waste could feasibly double food supplyand greatly reduce the environmental impacts of agriculture by halting further agricultural expansion into forest, grassland and wetlands (Foley *et al.,* 2011). In practice however, political instability, lack of infrastructure and the inability of poor farmers to invest in fertilizers, equipment and other inputs all constrain the impact of intensification in current low-yield regions (Johnson *et al.,* 2014). As a result FAO predicts that the average annual increase in global yields for wheat, rice and maize between 2007 and 2050 will be less than half of the increase achieved between 1961 to 2007 (Alexandratos and Bruinsma, 2012).

While the new technologies of molecular genetics and genetic engineering will undoubtedly help to increase the efficiency of crop improvement programs to boost future global crop output with adaption to a changing climate (Raghuvanshi and Singh, 2015) the focus of global food production is shifting from cereals as staples to the efficient supply of a protein-rich diet based on livestock products (FAO, 2013) particularly as household incomes increase. Demands for red meat, which are predicted to more than double during the next 20 years (Thornton, 2010) provide opportunities for grass-based ruminant producers, especially the 1 billion smallholder in the developing world, to use their livestock enterprises as a pathway out of poverty (McDermott *et al.* 2010) and as an important contribution to global food security (Herrero and Thornton, 2013). However, trying to satisfy future meat and milk demand using a business-as-usual production model will only exacerbate the already serious environmental damage caused by livestock systems evident in land degradation, biodiversity loss, soil erosion and greenhouse gas emissions (FAO, 2006a; Havlik*et al.* 2014). Rather, to achieve a sustainable livestock sector requires a refashioning of the livestock sector to deliver better nutritional outcomes with more efficient production using the same resources but at less environmental cost (Garnett, 2014).

In broad terms, achieving sustainable livestock production requires actions to: efficiently increase productivity; conserve, protect and enhance natural ecosystems; modify population growth and resource intensive consumption patterns; improve systems of governance; protect and improve rural livelihoods and social well-being; and reduce waste (FAO, 2014a; Charles *et al.,* 2015). In this review we willfocus on one of the challenges of sustainability: the potential for a significant, sustainable increase in production by improving livestock productivity, resource use efficiency and fair market access.

We do this by first defining what is meant by 'sustainability' and 'sustainable livestock production' as there are different views on what it is and how it might be achieved. We then analyse the demand-supply interactions in the global livestock sector to identify the drivers that influence the potential to refashion systems to efficiently meet growing demands for animal products and avoid further environmental change. To investigate the demand side, we review how the global trends in the production of animal products are responding to income-driven changes in dietary patterns. For the supply side, we assess the current status of global grassland resources and consider how the environmental damage already inflicted by past mismanagement and future impacts of climate change limit their capacity to support sustainable livestock systems or respond to different management practices. Finally, we propose how sustainable intensification strategies based on new technologies, practices and production systems can achieve a better demand-supply balance so that smallholders can produce 'more from less' while improving environmental benefits.

Sustainability: definitions and assessment methods

Definition

Sustainability has become the concept used by individuals, organizations and nations to assess and monitor human impacts on the natural environment and resource base. The World Commission on Environment and Development (UN, 1987) defined sustainable development as "development which meets the needs of current generations without compromising the ability of future generations to meet their own needs". This implies that resources are finite, should be used conservatively, wisely and consider long-term priorities and consequences. Sustainable livestock development should conserve land, water, plant and animal genetic resources, and be environmentally non-degrading, technically appropriate, economically viable, socially acceptable and have responsible animal ethics.

Dimensions of sustainability

The goal of sustainable development is to create a more resilient and environmentally stable system that produces more food (Allievi*et al.,* 2015) with *efficiency, sufficiency and consistency* (Huber, 2000; Garnett, 2014).

Efficiency is a supply side term, defined as the use of resources to produce the best possible economic output (Allievi*et al.,* 2015). Sustainable intensification of livestock production through appropriate technology transfer (increasing forage yield or improving grazing utilisation of forage) to low-producing nations increases the efficiency of global meat production (Tilman*et al.*, 2011) and can significantly reduce emissions per unit of production (Garnett, 2011).

A sufficiency, demand restraint perspective puts an onus on consumersand companies who promote unsustainable consumption patterns of high impact foods or services to change their behaviour (Garnett, 2014). Sufficiency targets that specify the appropriate amount for ideal human health have been suggested for sustainable global meat consumption to reach environmental and societal sustainability targets (Allievi *et al.*,2015). In practice, total supply of meat per capita is a useful indicator to measure progress towards sufficiency, acknowledging the different consumptions patterns that apply in *e.g.* the USA *vs* India.

Consistency or system transformation measures the capacity of human-made systems to replicate natural systems. If the man-made system closely mimics the natural system then this would lead to sustainability (Allievi *et al.*, 2015) acknowledging that natural systems have boom/bust cycles. Consistency as a measure would concentrate on green innovations such as sowing productive pasture species to replace or augment degraded grassland. Allievi *et al.* (2015) include animal welfare ethics in consistency; because animals can suffer in factory farms, humans may turn to vegetarianism which would significantly change sustainable development targets reflected in the key indicator of number of animals slaughtered per capita.

These three strategies are linked to sustainability and are interrelated. For example, an increase in efficiency may lead to greater consistency because gains in the amount of valuable meat produced by each animal would result in fewer animals being needed to satisfy the same level of consumption (Allievi *et al.*, 2015). This indicates that a composite approach using all three perspectives is needed to reliably assess progress made toward achieving a globally sustainable livestock sector. It is acknowledged though that tight regulation is unlikely within free markets.

Global meat production and consumption: Trends and challenges

Demand-driven global production

Worldwide meat production has almost quadrupled from 78 to 311 Mt, from 1963 to2012.About 25% is derived from cattle, sheep and goats (FAO, 2014b; Figure 1). The OECD/FAO (2014) estimates that global meat production will increase 19% by 2023 and that developing countries will account for 78% of the additional 57 Mt produced, much of this is driven by increasing household incomes. Poultry (49%) and pork (29%) account for most of this predicted increase; developed countries will contribute only one-third to the total poultry and pork increase. Poultry is the fastest growing segment of global livestock production because it is cheaper, more efficient to feed than other livestock, requires less land than other meats and there are few religious or cultural limitations to eating chicken. By 2020 poultry production will exceed pork production (Heinrich Böll Foundation, 2014). Almost all of the predicted increase in beef, sheep and goat meat production will come from the developing world. Beef production is scarcely growing in the United States and Europe, but production from India, Brazil and Australia, which together account for 59% all the beef exports, is expected to continue to grow. By 2050 global meat production is predicted to exceed 455 Mt with increasing contributions from developing countries (Alexandratos and Bruinsma, 2012).

Over 1963-2012, milk production has more than doubled from 340-792 Mt (Gerosa and Skoet, 2012). Due to the rapid expansion in smallholder milk production and the emergence of small-scale rural processors, milk production has become a major livestock activity in developing countries. Since 1970, India’s milk production has increased nearly six-fold (21-117 Mt).In 1997, India exceeded the United States in dairy production, making it the world’s leading milk producer (FAO, 2006b). In South Asia, milk consumption grew by an average of 3-4% per year (1995–2005) double the growth rates recorded for staple foods (Hemme and Otte, 2010). In the past, increased demand for milk was driven simply by population growth, whereas demand is now increasingly driven by rising per capita milk consumption in developing countries.

The growth in meat and milk production is driven by the rapidly increasing demand for livestock products concentrated in developing countries that have experienced rapid population growth, urbanization, changes in lifestyle and increasing disposal income (Thornton, 2010). As per capita income increases consumers reduce their use of staples and increase their consumption of animal protein (Zulauf, 2015). Income driven dietary changes have been most dramatic in Asia where total protein supplied from livestock products has increased by 140% since 1980 (FAO, 2006a). This pattern is set to continue, especially in China and India because of the huge demands of their new middle class. The sheer size of China’s population, the strength of their economy and the huge gap in consumption between the rural poor and richer urban consumers,

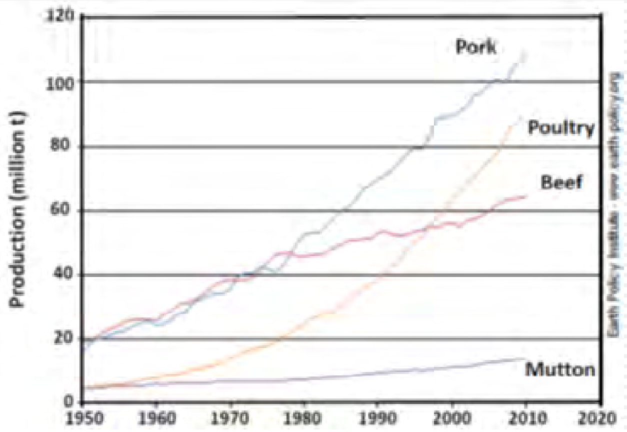

Figure 1. World meat production by type, 1950-2010 (Source: Worldwatch, FAO).

means the China food market with continue to rapidly expand as the income level of the poor increase (Zhou *et al.* 2012).

Production follows demand for meat, with South and East Asia undergoing the same rapid transformation from subsistence to market-oriented livestock production systems that occurred in many industrialized countries decades ago (Heinrich Böll Foundation, 2014). As the world's largest meat production country, China is using its economic strength to improve productivity and efficiency similarly to that previously done in the developed world. It is unlikely though that China can meet all the increased demand from domestic production, which creates opportunities for exporting nations to supply their 'diet gap', with inevitable effects on global food prices. However it is not clear that China could satisfy its increasing demand for meat from imports as the vast quantities anticipated are beyond the capacity of the main exporting countries.

Changes in consumption patterns

Worldwide consumption of meat has increased from 22 to 40 kg per capita between 1961 and 2012 (FAOSTAT, 2014). Most of this increase has occurred in developing and emerging economies where consumption of beef and veal, pork and poultry has grown around 3% annually since the mid-1990s; consumption growth has been only about 0.4% p.a. for developed countries (Westcott and Hansen, 2015). Developed countries consume an average of 64 kg/capita/y compared to 24 kg/capita/y for developing countries (FAOSTAT, 2014). The largest difference is between the current per capita consumption for the USA of ~117 kg/y, twice that of China and 30 times that of India (~4 kg/y) the world's lowest per capita meat consumption (FAOSTAT, 2014). With a total meat consumption of ~71 Mt, China now consumes more than twice as much meat products as the United States. In Africa supply and demand for meat are not growing as fast as in other parts of the world; Africans consume only 20 kg of meat a year, with little change expected over the next decade (FAO, 2014c).

Overall, the consumption patterns of poultry, pork, beef and sheep are not expected to change with aggregated consumption in developing countries, but with a continuing weakening trend among high income earners in developed countries over the next decade. Developing countries will account for 83% of the extra meat consumed in 2023, with Asian countries consuming half of it(OECD/FAO, 2014). Consumer preference across the globe supports higher growth of poultry compared with other meats, although expectations are that consumption of poultry is likely to be replaced with beef among high income households in developing countries, especially China. In contrast, poultry consumption in the United States is likely to increase by 12% to 57kg/person/y. Poultry consumption may rise in the countries where pork is not eaten (Malaysia, Israel, Middle East countries) depending on the beef and sheep meat prices. Pork which has ranked first in consumption, will lose market share particularly in the Asian market where consumers are diversifying to alternative meat products (OECD/FAO, 2014). Global beef consumption will remain stable, but with a slightly fall in per capita consumption in developed countries and slight rise in developing countries. Sheep meat will represent only a small share of the global meat market. The most significant growth in sheep meat consumption will be in Africa, China and countries in the Middle East (OECD/FAO, 2014).

Globally, the per capita consumption of staples is declining as household incomes increase, but the rising human population means that increased grain production will be required and there will not be a crop surplus to divert to animal production. Increased production of grains and forages will be needed to feed livestock, especially pigs, poultry, dairy cattle and some beef, sheep and goats. The standards for animal feed are not as restricted as for humans, hence it is easier to increase crop yields for livestock, but there is limited 'new' land suitable for crop production, particularly in Asia. This will probably mean a reduction in land used for grazing livestock, with the more productive land being used for crops. Increasing pressures will increase the costs of production that may slow the rate of meat consumption, though past evidence has not suggested this is a large effect. At present only ~10% of total world meat production is traded internationally (30.2 Mt, 2013 data; FAO, 2014b). While, poultry and pigs will be a large part of increased supply and demand in the future (being fed largely from crops), the increasing trend for more red meat consumption per capita will place considerable pressure on pastoral lands. Various trade agreements and increasing health and safety concerns mean that developing countries such as China may restrict imports to some countries (Australia, New Zealand, Canada, Brazil, EU) placing further pressure on their resources.

Global grassland and forage resources: distribution, status, use and threats

Grasslands cover more of the Earth's land than any other major vegetation type and are important for human societies, providing critical ecosystem goods (food for grazing animals, such as cattle, sheep, goats, camels; wildlife habitat; medicinal resources) and services (climate change regulation; genetic resources; erosion control; water provision; air purification; cultural and amenity services) at local, regional and global scales. We depend on grassland ecosystems to sustain us, but the continued health of these ecosystems depends in turn, on how they are used and managed. But, due to overgrazing by livestock and extensive clearing for crop production and more recently for biofuel production, many grasslands are now among the world's most endangered ecosystems (Blair *et al.* 2014). Here we review these land use changes, particularly their impacts on the global environment.

Defining grassland resources

Grassland resources are surprisingly diverse and difficult to define (Blair *et al.* 2014) because the term 'grassland' has evolved to now embrace 'all land committed to a forage use' which may be pastureland, forestland, cropland and rangeland as grassland resources (Allen *et al.,* 2011).

The vegetation of grassland in this context includes grasses, legumes, other forbs and woody species that may be indigenous or exotic and may occur as a monoculture (forage crop) a mixture of two or more species (sown pasture) or a rich and diverse plant community with over 400 species of forbs and woody plants present (Blair *et al.,* 2014). Grasslands may be temporary sown pastures integrated as leys in crop rotation systems or permanent natural ecosystems used for grazing by livestock and wildlife *e.g.* the savannahs of Africa, the grasslands of Australia, the cerrado, campo, llanos and pampa of South America, the prairies of North America and the steppes of Eurasia (Archibold, 1995). In much of Europe, natural grasslands are almost absent; remnant reserves are anthropogenic and need management to inhibit reversion to forests (Tscharntke *et al.,* 2005). A critical step in improving the way grassland ecosystems are managed is to audit their extent, monitor their condition and assess their capacity to provide the goods and service the world needs now and in the future (White *et al.,* 2000).

Distribution of grassland ecosystems

The global distribution of the ~5.4 billion ha of grasslands (~40% of the world's land area; White *et al.* 2000) extends to every continent, all ice-free latitudes (Figure 3) and in altitude range from coastal to montane regions at elevations above 4,000 m. The climates of grasslands vary from temperate to tropical with annual rainfall ranging from below250 mm/year in arid grasslands to well over 1,000 mm/year in mesic grasslands. Mean annual temperatures vary from near 0^{o}C to above 25^{o}C. Seasonality of precipitation, soil factors, herbivory and fire are additional important factors in determining local vegetation composition and structure.

This wide climatic and topographic range make grasslands very diverse ecosystems. Sub-Saharan Africa and Asia have the largest total area in grassland, 14.5 and 8.9 Mkm^2, respectively (Figure 2).Five countries (Australia, the Russian Federation, China, USA and Canada) each have more than 3 Mkm^2 of grassland (White *et al.* 2000). There are 28 smaller countries (25 in Africa) where grassland accounts for >60% of their total land area. Of those 28, five countries contain more than 1 Mkm^2 of grassland (Mongolia, Kazakhstan, Angola, South Africa,Ethiopia).

Of the grassland biomes, savannah, shrub land and grassland account for >80% of the grassland resources (Figure 3). Specific grassland types such as sown pastures form significant parts of the grassland biome as well as significant parts of tropical and temperate forest biomes (Alkemade *et al.,* 2013). Rangelands which are located mostly in semiarid regions too dry to sustain agriculture, are often used as a category similar to grasslands but do not include sown pastures and are generally grazed using low-input systems.

Loss of grassland ecosystems through conversion to agriculture

Human action has profoundly changed the extent, distribution and condition of all major ecosystems on earth. Conversion to croplands and other agro ecosystems has been the main cause of the loss of grasslands globally. Temperate grasslands with better soils and more frequent rainfall have been mostly cleared for crops by the 1950s (Millennium Ecosystem

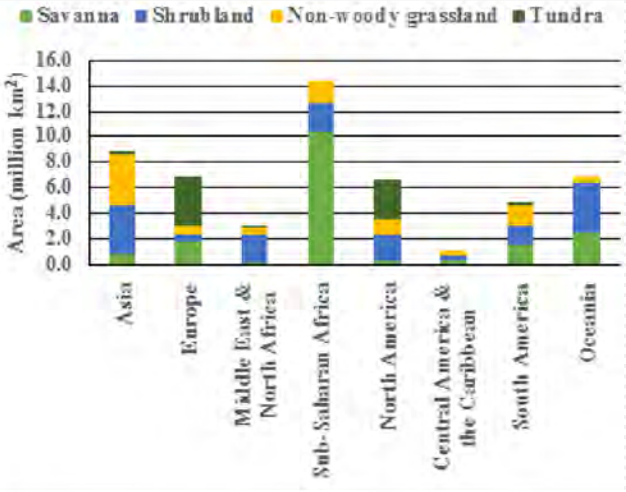

Figure 2. Area (Mkm^2) of grassland biomes in world regions (White *et al.* 2000)

Assessment, 2005) whereas poorer quality semi-arid grasslands were left for grazing livestock (Suttie *et al.*, 2005) until recently when new technologies such as minimum tillage and drought tolerant species have made it feasible to grow crops profitably in drier environments (Clay *et al.* 2014). This means that the current and future threats to grassland ecosystems are high as the agricultural sectors in South America (Gavier-Pizarro *et al*. 2012) southern Africa (Maeda *et al*. 2010) North America (Landis and Werling, 2010) and Asia (Qiu *et al*. 2010) expand to feed a rapidly growing human population (Foley *et al.* 2011). Grasslands are not always recognised for their intrinsic value, but as lands that will one day be intensively exploited.

Conversion to croplands, mixed farming and sown pastures has affected some 3.3 billion ha, 26% of the world's land area and represents a loss of one-third of temperate and tropical forests and one-quarter of natural grasslands (*Töpfer et al., 2000)*. To date, the loss through conversion has been greatest in developed countries. For example, in the United States over 97% of tall grass prairie, 71% of mixed prairie and 48% of short grass prairie had been lost by 2003 (Robertson *et al.* 1997; Samson *et al.* 2004). Similar conversion took place in Canada with tall grass prairie, North America's most threatened prairie (Sampson *et al.* 2004) now covering only ~100 km^2 of its former 6,000 km^2 in Manitoba (Joyce and Morgan, 1989) and 820 km^2 in Ontario (Ontario Ministry of Natural Resources, 2009). In selected grassland eco-regions, conversion to croplands has been as high as 76% in South America and from 20% to 40% in other regions (*Töpfer et al., 2000)*.

The Millennium Ecosystem Assessment (2005) scenarios predict that a further 10-20% of grassland and forest resources will be converted, primarily to agriculture before 2050 concentrated in developing countries, encompassing both dry and tropical regions. A small increase in forest cover is predicted for developed countries as part of greenhouse gas (GHG) abatement programs.

The economic gain and long-term sustainability of improved food production on land converted from grassland must be balanced with the loss of services provided by grasslands. Crop production in semi-arid regions, for example, has already been challenged with dryland salinisation resulting from water imbalance that causes the rising water table to transport subsurface salts to the surface soil (Clay *et al.* 2014). In Western Australia the replacement of deep rooted shrubs by annual cereal and oil crops has already caused large increases in dryland salinity; predicted to exceed 17 Mha by 2050 (National Land and Water Resources Audit, 2001). Salinity now affects>4.5 Mha of dry-land cropping in the Canadian prairies (Wiebe *et al*., 2005). Urbanisation and transport infrastructure further encroach on grasslands and now occupy more than 471 Mha or ~4% of the land area.

Current state of grazed grasslands

Indicators used to determine change in grassland condition include: shift in species composition, loss of biodiversity, reduction in biomass production, less plant cover, low small ruminant productivity, erosion and changed soil properties evident in acidification and reduced water infiltration. The first signs of change in grassland condition due to overgrazing are reduced production and species shifts with, typically, the more palatable perennial grasses being replaced by less palatable species *e.g.*shrubs. On this basis, condition of the world's grassland resources is varied but in many cases is far from satisfactory (Suttie *et al*., 2005) as portions of all grassland types on every continent have been degraded, mostly as a result of inappropriate stocking rates and grazing management practices.

On a global basis, Conant (2010) categorised ~20% (or 685 Mha) of grassland resources as degraded *i.e.*grasslands that will require serious intervention to recover. A disproportionately large share of the degraded grassland has occurred in the developing world with the most extreme degradation affecting Africa (243 Mha), Asia (197 Mha) and Latin America (78 Mha) (Global Land Assessment of Degradation, GLASOD). From the GLASOD study, Scherr and Yadav (1996) predicted that vegetative degradation of grasslands would accelerate by 2020, as a result of

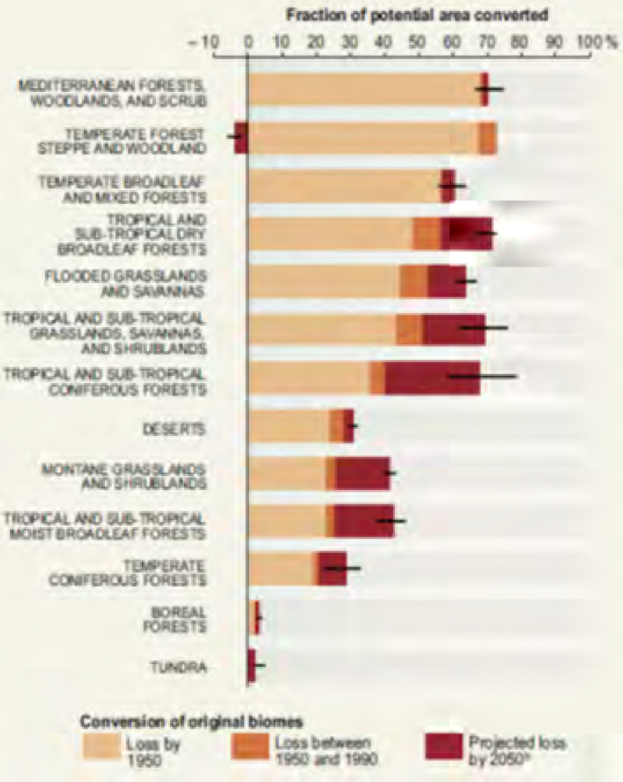

Figure 3. Area of key biomes estimated to have been converted up until 1950, between 1950 and 1990 and how much is predicted to be converted under the Millennium scenarios between 1990 and 2050. (Source: Millennium Ecosystem Assessment, 2005).

overgrazing and over-exploitation of vegetation for fuel, in the trans-Himalayas and in Southern and North Africa, whereas the spread of *Imperata* would be the key driving force for degradation in Southeast Asian grasslands. These predictions are coming to pass with overgrazing becoming an even more important degrader of grassland condition across all grassland types.

Environmental challenges and opportunities for grass-based livestock production systems

Grasslands present a vast and readily exploited resource for domestic grazers (Blair *et al.*, 2014). Since the fate of smallholder pastoralists living in these areas is intimately tied to livestock production dependent upon grasslands, any significant change in grassland condition can directly harm livelihood. Indirect harm to a larger population occurs through biophysical (dust storms, greenhouse gas emissions and regional climate change) and socioeconomic impacts. Understanding the impact of grazing-induced degradation on the environment is crucial to developing sustainable production systems and rehabilitation programs for degraded grassland systems. The impacts discussed here include: reduced biomass, loss of biodiversity and changes in carbon stocks and GHG emissions.

Managing biomass production and vegetation cover

The ability to inventory ground cover and standing biomass over large landscapes is central to mapping impact of overgrazing on grassland condition. Wolf *et al.* (2015) calculated global livestock feed intake in 2011 to be ~4.84 Pg DM, 52% of which was grazed from grassland and pasture resources and the balance from crop residue (12%) and feed-crop (36%) to produce 0.26 Gt of meat in our modern global agricultural systems (Smith *et al.*, 2013). Despite the increasing reliance on grain, occasional feeds (cut-and-carry forages and legumes and roadside grasses) and crop stover, grasslands are still the key feed resource for ruminant grazing and mixed crop-livestock systems (Herrero *et al.*, 2013a).

Over coming decades, the combined effects of intensity of use and climate change will affect the productivity of the grasslands and forage crops (Ghahramani and Moore, 2015) that underpin the feed-base for livestock production systems. At constant CO_2 levels, Weindl *et al.*, (2015) predict an overall global decrease in grassland yield of 2% with the strongest negative effects in Australia (-11%) and in the Middle East and North Africa (“28%). For a native subalpine *Festuca idahoensis* ecosystem, Brookshire and Weaver (2015) reported a decline in above ground net plant production of >50% over the last 44 years, at an average rate of ~-2.5 $g/m^2/yr$. They attributed this to increased global temperature and altered precipitation patterns that reduced the capacity of grassland ecosystems to provide goods and services. Additional losses due to pest and weeds are predicted to increase from the current average level of 13% of forage growth (Bajzelj *et al.*, 2014). Drier climates would be expected to lead to changes in botanical composition to less productive and, or less palatable plant species, as seen with the increase in *Stipa* and, or *Artemisia* spp. in Chinese grasslands.

Identifying the prime causes for declining biomass production and the biophysical processes involved is crucial to formulating remedial management solutions. Time series of remote sensing data is a useful method to evaluate grassland dynamics at broader scales, especially with MODIS providing near daily coverage at 250 m to 1 km resolution. Using these tools, Hilker *et al.* (2014) was able to determine that at a landscape level about 80% of the decline in biomass in Mongolia is attributable to increases in livestock whereas precipitation explained <30% of variation across the country as a whole, but up to 50% in areas with denser vegetation cover. Using similar methods, Gang *et al.* (2014) identified climate change as the principal influence that explained 46 % of global grassland degradation, with southern hemisphere grasslands (Australia) more vulnerable and sensitive to climate change. This means that maintaining the balance between grassland and forage supply and livestock demands is fundamental to sustainable livestock systems. Grazing animals affect grassland condition by altering plant (cover type, density and height) and soil properties (compaction, runoff, erosion and C and N cycling) through grazing and the physical action of their hooves with the magnitude of the changes determined by grazing intensity and grassland type. Some grasslands (tall grass prairies of North America or the Serengeti grasslands of Africa) appear to be well adapted to relatively high grazing intensities, though this may only apply for short periods each year, whereas other grasslands can be quickly degraded by overgrazing (Blair *et al.*, 2014).

For all grassland types, maintaining both green and dry biomass within boundaries determined by livestock performance is the primary criterion for managing grasslands (Kemp and Michalk, 2007). For example, the general relationship between sheep or cattle growth and green herbage indicates that biomass needs to be maintained around 1.5-2 t DM/ha to achieve 90-95% of maximum live weight gain (Kemp *et al.*, 2015a). In practice, this means stocking rates need to be continually adjusted to optimise livestock productivity and the other environmental service grasslands provide. Degradation is evidence of a management failure to balance livestock feed demands with the capacity of forage resources to supply these demands (Kemp *etal.*,2015b). Climate changes with predicted increasing frequency of droughts and extreme rainfall events, will pose greater challenges to manage pastures and sustain the feed supply for livestock.

Many of the symptoms of reduction in biomass and vegetation cover are common, irrespective of the cause of grassland degradation. If not managed properly, grasslands can be easily overexploited with subsequent reduced productivity and loss of key species (perennial grasses) due to a decreased capacity to retain water, increasing erosion by modifying surface soil stability and exporting nutrients and sediments to downstream water resources (McIvor *et al.*, 1995). In Asia, for example, more than two Mha of grasslands are being degraded every year through water and wind erosion as a result of increased pressure from livestock production. However, when managed using practices that sequester carbon in grassland soils such as retaining a minimum of 70% of surface cover (Sanjari *et al.*, 2009) or > 2t DM /ha of biomass (Hughes *et al.*, 2006) a grassland effectively controls soil erosion because it reduces raindrop impacts, aids infiltration rate by preventing surface sealing and traps sediment and filters water through surface vegetation to produce good quality runoff (Haregeweyn *et al.*, 2013). Using these management guidelines to retain grassland cover in mixed livestock-crop systems in temperate Australia has produced a six-fold reduction in the dust storm index from 17.7 to 2.9 (McTainsh*et al.*, 2011). As watershed cover, well-managed grasslands are crucial to increase hydrological and erosion safety which makes the quality of water production an important product derived from grasslands.

In grasslands with sufficient productive potential, pasture intensification measures such as the sowing of improved and deeper rooted grass and legume species can significantly increase forage productivity and quality relative to natural grassland, although significant costs are incurred in lost production during establishment and if inappropriate stocking rates are used there will be a decline in productivity over time (Kemp and Dowling, 2000). However, there are effective and economic options to manage the perennial grass composition to a more desirable state, including improved grazing management, fertilisation and herbicides to control weeds (Kemp *et al.*, 2000). These practices can align with tactical management to better match livestock demand and feed supply. Simple grazing management tactics have often shown benefits, but must be targeted to individual key species because each species responds differently depending on their phenology, response to grazing and competition with associated pastures species (Kemp *et al.*, 2015b).

Loss of biodiversity

Agricultural biodiversity includes all the components of biological biodiversity relevant to producing food and to sustaining the key functions of the agro-ecosystem. As such, agricultural biodiversity includes the variety and variability of animals, plants and micro-organism at the genetic, species and ecosystem levels; biotic factors; and socio-economic and cultural factors (Hoffman, 2011). Grasslands are among the world's ecosystems with the highest richness (Wilson *et al.*, 2012) but balancing retention of biodiversity and ecosystem function with biomass production to sustain livestock is a global challenge.

Failure to achieve this balance by continual increases in livestock densities means that ~30% of biodiversity loss is linked to livestock production through grassland degradation caused either by overgrazing or through deforestation and conversion of land for forage-crop production (Westhoek *et al.*, 2011). The livestock related processes that cause habitat fragmentation, desertification and competition from alien species now threaten biodiversity in ~300 of the 825 terrestrial eco-regions and 23 of 35 global diversity hotspots (FAO, 2006a). Species losses of this order have shifted the functional composition of the vegetation, evident in widespread replacement of perennial grasses by fast growing forbs, annual grasses and woody shrubs cascading to soil food webs (density and diversity of soil organisms). This alters numerous ecosystem functions and depletes environmental services (Lavorel & Grigulis 2012).

In grassland landscapes, maintaining the desirable perennial species biomass through appropriate grazing management is the best way to enhance community stability, retain biodiversity and deliver multiple ecosystem services which are highly dependent on the natural productivity and management of grasslands (Petz *et al.*, 2014). Inevitably, since livestock graze selectively, some species will be defoliated more intensively which reduces their competitiveness against less desirable species and invading weeds. Since a few abundant species usually account for a large fraction of grassland biomass within both natural and sown grassland communities, it is often thought that the many rare species present have little impact on ecosystem function. It is important though, to note that the relationships between diversity and function are not linear and that a threshold in species richness exists below which ecosystem function declines and above which it does not change (Vitousek and Hooper, 1993).

Biodiversity needs to consider plant function, more so than total species numbers (species richness). A series of experiments across southern Australia (Kemp *et al.*, 2003) found that grassland productivity declined and variability in productivity dramatically increased, as species number increased. This suggested there is an optimal number of species, though the curve showed a general decline, rather than any clear optimum for productivity – other functions need to be assessed to help identify the optimal plant structure. Many of the species found in this study were minor forbs, annual monocotyledons and others that collectively formed a few plant functional types, suggesting a high degree of species redundancy. These groups typically contributed only 1-5% of total net primary production over a year. Productivity was determined by only a few species, notably native or introduced grasses. Among the minor species were several that would be considered invasive weeds. As grazing pressures increased, so did the number of species, primarily minor ones. The conclusion was that biodiversity should be assessed on a plant functional type basis. Further analyses showed that the desirable native grasses that had the larger effect on plant productivity could be maintained within the sward if the herbage mass throughout the year was maintained at 2 t DM/ha or above. More native species survived in these grasslands where the total species number was low, implying they were not very competitive against those species that invaded grasslands under higher grazing pressures.

The optimal species number, or plant functional type number is not always clear, but what has emerged from studies such as Kemp *et al.* (2003) is that the more productive functional type (typically the desirable perennial grasses) needs to be at least 60% of the total biomass in order to exert competitive pressures on invasive weed species. The corollary being that invasive weed species should be maintained below 10-15%. The balance (25-30%) should then be legumes, and other forbs, plus ‘gap fillers’ (short-lived annuals) to aid productivity and maintain a desirable composition. A combination of several plant functional types does provide stability and did not show any adverse impacts on soil micro- and meso-organisms (Kemp *et al.*, 2003).

Monospecific swards are clearly difficult to manage and can create other problems. For example, Franklin *et al.* (2006) reported that the environmental degradation caused by introducing buffelgrasswas not balanced by increased productivity of rangelands in Sonora, Mexico. Buffelgrass displaced native species and provided fuel for fires in these habitats, which severely reduced populations of trees and columnar cacti upon which many bird and insect species depend.

The reduction in the diversity of livestock breeds used for breeding in the global cattle and sheep industries due to dominance of a few highly productivity specialised breeds (Friesan-Holsteins, Angus, Simmental) is threatening indigenous ecotypes (Stoll-Kleemann and O’Riordan, 2015). FAO (2007) reports 9% of the original global farm animals are already extinct and more than 20% of the remaining germplasm is under threat. This is a consequence of poorly designed cross-breeding systems which use exotic imports and place scant attention on maintaining purity of indigenous genetic resources, the vast majority of which are kept by smallholder farmers under traditional management systems (Ayalew *et al.*, 2003).

This has contributed to the erosion of local breeds adapted to survival under low input mixed farming and pastoral production systems found throughout the developing world (ILRI, 1999).

Hotspots where biodiversity is most threatened are located in the Sahel, Pakistan, West India, Middle East, North Africa and parts of Brazil where the highest grazing intensity is combined with traditional management (Petz *et al.* 2014). At the same time, these low-input systems of poor farmers rely more strongly on biodiversity and the associated ecosystem processes such as beneficial tropic interactions, soil food webs and stress-adapted crop genotypes for their grasslands to remain partially functional (Jackson *et al.* 2007). However, with appropriate technology, skills development and market access smallholders in these hotpots can improve their profitability and sustainability (Tscharntke *et al.*, 2012).

Managing GHG emissions and climate change

Globally, livestock consume 17 Gt CO_2e/y-of feed made up of 4.4 Gt CO_2e/y-from crop production, 2.6 Gt CO_2e/y-from crop residues and 10.0 Gt CO_2e/yr from grassland and forage resources (Bajzelji *et al.*, 2014) and are responsible for 14.5% (Table 1) of the world's total anthropogenic GHG emissions of 49 Gt CO2e/yr (Ripple *et al.* 2014) and 70% of total emissions from agriculture (Tubiello *et al.*, 2013). Ruminants account for 11.6% of global GHG emissions from all anthropogenic sources, 90% of which are contributed by cattle (Table 1). The majority (44%) of the GHG contribution from livestock is in the form of CH_4 emitted through enteric fermentation and manure, with the balance from CO_2 emitted through land use change and fossil fuel use (27%) and N_2O from fertilizer applied to feed-crop fields and manure (Ripple *et al.*, 2014). Between 1960 and 2010 global CO_2e emissions from the livestock sector increased by 51% (Caro *et al.*, 2014). Due mainly to increases in beef and dairy cattle numbers emissions rose by 117% in developing countries but fell by 23% in developed economies.

Deforestation, mostly in tropical areas due to expansion of pasture and arable land for animal feed crops, degradation of native grazing lands and conversion to cropland (palm oil in south-east Asia) are responsible for a significant proportion of global greenhouse gas emissions from the livestock sector estimated at losses of 450 800 Gt CO_2 from biomass and soil carbon pools (Olofsson and Hickler, 2008; Shevliakova *et al.*, 2009). Lowering demands for beef or improving production efficiency of the current cattle herd would eliminate the need for further tropical deforestation, as well as generating substantial benefits from other biomes and processes (Ripple *et al.* 2014). Total elimination of deforestation by 2030, for example, could theoretically deliver a mitigation potential of ~2.3–5.8 Gt CO_2e/y.

Net carbon sequestration in soil and vegetation in grassland through better land management is a proactive mitigation pathway with a potential of ~1.5 Gt CO_2 e/yr to 2030 with additional mitigation possible from restoration of degraded lands with a C sequestrate rate of 0.04 to 1.1 Gt CO_2e/yr (Smith *et al.*, 2007). However, since plant growth in grazing lands is often co-limited by water and N (St Clair *et al.*, 2009) grasses place up to 87% of their net primary production belowground to capture these resources (Fan *et al.*, 2009). This means that any global change drivers that alter-the water and nutrient regimes may change plant growth and biomass allocation thereby placing uncertainly on grasslands and savannahs as a C sink (Lee *et al.* 2010). However in the near future, as many grasslands are considered degraded, practices that encourage rehabilitation and increased productivity of grasslands are likely to show major benefits for carbon storage and GHG mitigation.

In both temperate and tropic environments sowing pasture species that are better adapted to the local climate, more resilient to grazing, more resistant to drought and able to enhance soil fertility (*e.g.* N-fixing species) can lead to increased production and forage quality. Soil C sequestration is reversible and C can be rapidly lost through a number of processes associated with climate variability and poor management such as

Table 1.Livestock sector GHG emissions in Gt CO_2e/y (adapted from Ripple *et al.* 2014 using FAOSTAT data for 2011).

Livestock number/Source of GHG emissions	**Ruminants**			**Monogastric[3]**	**Total**
	Bovine[1]	**Ovine[2]**	**Total**		
Total number (billion)[4]	1.6	2.0	3.6	20.0	23.6
CH_4 emission (Gt CO_2e/y)	2.29	0.22	2.51	0.62	3.12
CO_2 emission (Gt CO_2e/y)_	1.40	0,14	1.54	0.38	1.92
N2O emission (Gt CO_2e/y)	1.50	0.14	1.64	0.41	2.06
Total emission (Gt CO_2e/y)	5.2	0.5	5.7	1.4	7.1

Notes: [1]1.4 billion cattle & 0.2 billion buffalo; [2]1.1 billion sheep & 0.9 billion goats; [3]19 billion poultry & 1 billion pigs; [4]FAOSTAT data for 2011.

soil disturbance, vegetation degradation through overgrazing, fire, erosion, nutrient shortage and water deficit (Soussana *et al*., 2014). It is a realistic expectation that ~10% of global grazing lands could be placed under C sequestration management by 2020 (Conant, 2010).

Although grazing livestock contribute significantly to climate change, it is feasible to make livestock production systems part of the mitigation solution by changing management. Improved forage quality and feeding practices can help mitigate GHG emissions (Sirohi, 2015) but effectiveness of improved management depends very heavily on the *a priori* identification of areas amenable to these practices (Henderson *et al*. 2015a). For example, Thornton and Herrero (2010) showed that while a 10% improvement in digestibility of stover and increasing grain supplement from 0.5 to 2 kg/head/day both effectively reduced CH_4 emission in cattle, in practice treating crop residue is like to be more effective because it has wider application across most rain-fed mixed systems in developing countries where ~63% of cattle are raised (Gerber *et al*. 2013) and stover comprises 50% of the diet of ruminants (Herrero *et al*., 2013a) whereas feeding grain concentrates is an option that is most appropriate to the humid and temperate mixed systems.

While GHG emissions from livestock are substantial, a transition from extensive to more intensive and efficient livestock presents attractive mitigation opportunities to reduce GHG emissions per unit of livestock product, while at the same time increasing productivity by improving animal husbandry (*e.g.* less grazing and better quality feed; improved breeding; better disease control) improving grassland management practices and/or rehabilitating degraded grasslands (Havlík*et al*., 2014). This is good news for the developing world where the most of the degraded grasslands are found (Conant 2010); because sustainable intensification can play a key role in increasing production and improving environment performance. This does not mean that production should be increased uniformly (Charles *et al*., 2015); rather more work is needed to develop indicators, based on biophysical and management characteristics of grazing lands, to identify amenable areas before many of these practices are ready for large scale implementation by smallholders in the developing world (Henderson *et al*., 2015b). In some cases the amount of total livestock product could remain the same, but achieve GHG gains through improvements in efficiency.

The GHG debates have often focused on black or white scenarios, where arguments have implied that all livestock should be slaughtered and everyone becomes a vegetarian. That clearly ignores the reality of many countries, particularly those in the developing world. The way forward is to evaluate management options through efficiency measures such as the amount of GHG per unit of animal product. Developing countries have much room to make improvements by using those criteria.

What role for smallholders in this demand-supply livestock sector?

The solution to achieving sustainability of the global food system (*i.e.* a balance between demand and supply) requires either a reduction in consumption of livestock products and/or a significant increase in productivity gains (Havlik *et al*., 2014). This review has shown that on the demand side, aggregated global meat consumption is increasing on a continued upward trajectory driven by population and rising living standards. Projections indicate that an additional 144 Mt of livestock products will be needed by 2050 to meet this continuing strong demand. However, health concerns and relative prices have driven a trend whereby red meat has gradually been substituted by white meat in developed countries, but red meat consumption is still rapidly increasing in developing countries (Henchion *et al*., 2013). This is evident in projections that demand for red meat will account for 31 Mt of the 2050 demand; 25 Mt of which will come from developing countries (Alexandratos and Bruinsma, 2012).

On the supply side, the business-as-usual approach of land conversion cannot be used to increase livestock production as this will only magnify existing serious environmental problems (Havlik *et al*., 2014). Rather, increased production must be achieved by more efficiently using the forage, feed-crops and crop residues derived from land and water resources currently devoted to livestock production (World Bank, 2007). Possible strategies to achieve an increase in livestock product output include: increasing animal numbers and/or increasing productivity per animal (higher off-take rates, faster growth rate, higher carcase weight and greater milk or egg yields per animal) through improved efficiency (Herrero *et al*., 2013a). Projections show that increasing livestock numbers will remain significant, but less so than in the past (Table 2). Higher carcass weights achieved through better quality feed and feeding practices, improved genetics, health interventions and grazing management (Thornton and Herrero, 2010) will play a more important role in beef and mutton production to reach 2050 target carcase

Table 2. Meat production: number of animals and carcass weight (FAOSTAT; Alexandratos and Bruinsma, 2012).

Livestock type	Number of animals (millions)			Average carcase weight (kg)		
	1963	2007	2050	1963	2007	2050
	Developed countries					
Cattle & buffaloes	352	318	320	163	271	283
Sheep & goats	577	389	460	15	17	18
Pigs	248	288	294	71	87	92
Poultry	2568	5239	7212	1.3	1.9	1.9
	Developing countries					
Cattle & buffaloes	692	1215	1712	150	166	209
Sheep & goats	779	1526	2478	12	13	17
Pigs	176	629	846	49	74	81
Poultry	1867	13921	29817	1.1	1.4	1.6

weights, whereas higher off-take rates (shorter production cycles) will be more important in pig and poultry meat production (FAO, 2006b) and for grazing livestock in developing countries where the potential gains are much greater.

Even with improved technology and better market access, many question the sustainability of livestock farming which uses far more land and water resources than any other human activity and advocate dietary change with a significantly reduced meat intake as the only feasible way forward to address the many crucial environmental (GHG induced climate change) health (obesity) and moral (animal ethics) issues caused by the livestock sector (Stoll-Kleemann and O'Riordan, 2015). However, despite the catalogue of negative impacts evident in loss of biodiversity, high consumption of fresh water and greenhouse gas (GHG) emissions, there is growing recognition that making livestock central to the solution by improving the production efficiency and environmental performance of livestock systems rather than considering livestock as the problem is a better pathway to meet the challenge of feeding the world sustainably (Herrero *et al.*, 2013b). Humans are omnivores and their desire for meat is obvious.

Inevitably, when problems are global, the solutions are generally local and situation-specific (Herrero *et al.* 2013a). For this reason, smallholder livestock keepers, who number more than 1 billion and produce ~80% of the food supply in Asia and Africa and 40% of global agriculture gross domestic product are central to achieving global food security because the potential to improve their production efficiency using a sustainable intensification approach is far greater than in the developed world (Kemp and Michalk 2011, Herrero and Thornton 2013). But is it possible to achieve the twin aims of improving efficiency of smallholders in the developing world without increasing livestock numbers and at the same time improving environmental performance? Can we take principles and practices used to achieve eco-efficient livestock systems in the developed world and apply them to smallholders in developing countries? Where should we first concentrate our effort: in the countries where the hungry live or in the transforming countries (China, Vietnam and India) that have achieved the most rapid rise in GDP growth and where the increased demand for livestock products is highest (McDermott *et al.* 2010)?

Difference in production efficiency between developed and developing countries

Livestock production systems are shaped by the linkage between demand and resource supply. Demand reflects consumer expectations concerning food preferences, quality, variety and safety whereas supply includes the physical inputs (land, forage, livestock, labour and water) available technology, management skills, access to markets and capital (FAO, 2006a). The way these components are combined determines the productivity of livestock systems and explains the differences observed between geographic locations in the way livestock are raised and the impacts they have on the environment. The effect of the linkage between demand and supply is most evident in the dichotomy between developing and developed countries.

With livestock production growing strongly in developing countries over the past 35 years, but remaining static, albeit at a higher level, in the developed world (Thornton, 2010) one could conclude that a significant shift in production efficiency through intensification is already taking place in the developing world. However, statistics show that increases in ruminant production in developing countries is driven mostly by increasing the number of animals, whereas in developed countries the livestock population has remained constant, but the output/animal evident in carcase weight has increased significantly reflecting improved production efficiency (Table 2). More importantly, Table 2highlights a huge potential opportunity to achieve key sustainability goals through planned intensification, particularly in developing economics. It identifies a systematic threat of imbalance between forage supplies and livestock demands that, if uncorrected, will have repercussions on virtually all aspects of environmental well-being. The question is does this work in practice?

Australia's sheep industry: An example of 'more for less'

Industry-wide statistics for the Australian sheep industry clearly demonstrate the efficiency gains made possible through the application of sustainable intensification. In 1980, Australia had ~150 Msheep raised on 56,000 farms which produced a total sheep carcase weight (cw) of 530,000 cw t compared to 2012 when Australia had ~72 M sheep raised on 43,000 farms that produced 640,000 cw t (ABS, 1982; ABARES, 2013). This represents a 60% reduction in sheep numbers and 21% increase in sheep meat production, most of which is exported. A reduction in livestock numbers means that the available forage per animal increases, providing some of the productivity gains – often from animals being able to be more selective from pastures with more desirable species within those pastures. In addition, more use is made of forages like *Medicago sativa* for finishing lambs for the markets.

Selecting the best genetics, breeding systems and grass-fed management strategies have helped increase lamb carcase weight to 22 kg/head in 2012, 30% higher than the predicted carcase weight for2050 (Table 1). This achievement is due to investment in research focused on identified profit drivers for wool (*i.e.* clean fleece weight, fibre diameter, staple length, colour, strength and low contamination) and meat (*i.e.* reproductive performance, lamb growth rate, fat depth and meat quality) and development of precision management practices, including good agronomy, that consistently and efficiently produce sheep products that meet the demands of Australia's domestic and export markets (Michalk *et al.,*2015). Just as importantly, National programs such as Prograze (Bell and Allan, 2000) Sustainable Grazing Systems (Mason *et al*., 2003) Grain and Graze (Bridle and Price, 2009) and EverGraze (Badgery *et al*., 2015) have clearly demonstrated that many environmental benefits such as improved hydrology, enhanced species diversity and reduced erosion have positive outcomes on production with substantial financial benefits to people involved in grazing industries. Those programs have always had good agronomy and improved forage management as core components.

The potential impact of precision management on livestock performance is clearly evident in a comparison of the Australian and Chinese sheep industries. In 2011, the China sheep flock totalled 140 M with a total meat production of 2 Mt at an average carcase weight of ~16.7 cw kg/head for the 120 M sheep slaughtered (Chinese Statistics Yearbook, 2012). In contrast, Australia's sheep flock totalled ~72 Mand produced 640,000 t of meat with an average weight of 22 cw kg/head for the 29 M slaughtered (ABS, 1982; ABARES, 2013). If the Chinese sheep industry used the genetic selection tools, breeding systems and grazing management tactics that have revolutionised the Australian sheep industry (Michalk*et al.* 2015) the Chinse sheep flock could be reduced to 106 M and still produce 2 Mt of sheep meat by slaughtering 91 M with an average carcase weight of 22 kg/head. This represents a 25% reduction in the total sheep flock achieved through planned intensification. Sustainable intensification does not necessarily need more resources; it just needs better knowledge applied to managing the livestock system to increase the efficiency with which existing resources are used. *Transition from subsistence to market-oriented livestock production*

Developing strategies and tactics that better align the balance between forage supply and animal demands underpins the efficiency gains in the Australian sheep industry because the benefits of improved breeding and other husbandry are dependent on an adequate supply of quality forage. Since Australian ruminants are predominantly grass-fed, farmers now regularly assess the amount and quality (energy and protein) of feed-on-offer in sown forages and grasslands and adjust stocking rate so that nutritional requirements for animals are supplied. Grassland management aims to improve and maintain the desirable species and to minimise the need to resow permanent pastures. Special purpose forages are then used to maximise benefits in livestock for sale.

To achieve these industry-level productivity gains in the developing world requires a paradigm shift in smallholder production from a traditional to a market-oriented system (Michalk *et al.,* 2015). The foremost challenges in promoting sustainable livestock intensification is to change the mindset of smallholders from a subsistence to a business framework in which the focus shifts to where livestock are regarded as the saleable product derived from the feed supply resource (Wu *et al.* 2011). This then enables optimal solutions to be found between the number of animals and the available feed supply using an energy balance/market based approach (Kemp and Michalk 2011, Kemp *et al.,* 2013, Kemp *et al.*, 2015a, 2015b). The key relationship is one of diminishing returns: as the number of animals per unit area increases, the available forage per animal decreases which results in production per animal declining and production per hectare rising, then falling once animal production per head is half of their potential (Jones and Sandland, 1974). As explained by Kemp *et al.* (2015a) these relationships have important implications for determining sustainable, economically optimal stocking rates for grass-fed livestock systems that have stocking rates where the production per hectare is ~75% of the biological maximum.

Since many farmers (and especially smallholders) are grazing forage resources well beyond the economic optimum and since feed shortage is a major constraint common in most livestock production systems, it is possible to reduce animal number considerably by replacing low producing animals currently raised by subsistence smallholders with fewer but better-fed animals of a higher potential that produce more product and profit (Kemp *et al.*, 2011, 2013;Thornton *et al.*, 2011). Balancing livestock needs with current forage supplies will provide smallholders with the greatest opportunity to increase profit by producing more valuable products (Kemp *et al.*, 2011). This means that sustainable intensification does not depend on additional fodder inputs, but is achievable through more efficient use of the currently available feed supplies. At the same time, reductions in grazing pressure can start the rehabilitation process of grasslands severely degraded from over-grazing that are typical of traditional livestock systems (Briske *et al.*, 2015). Local research is needed to resolve which are the better grazing tactics and strategies to facilitate grassland regeneration.

This transition of smallholders to a market economy requires new skills to deal with the technology and decision-making that underpins the management of new livestock production systems within a commercial context. Impoverished herders have insufficient skills and knowledge to make decisions in a market economy as their skills reflect survival needs, and they are handicapped by a severe lack of market information (Liu 1998). This means the major challenge is identifying the appropriate technologies to underpin sustainable intensification and capacity development through tailored education and targeted training to build knowledge and self-confidence to a level where herders are willing to take the risk and apply new technologies to a competitive, market-oriented livestock industry about which they still have ignorance and uncertainty (Wu *et al.*, 2011).

Conclusion

Is there a sustainable future for the demand-supply driven world's livestock sector? This review agrees with other assessments (Thornton 2010; Herrero and Thornton, 2013) that demand for livestock products, driven largely by human population growth, income growth and urbanization, will continue for at least the next 30 years with increasing demand from the developing world. It is clear that sustainability cannot be achieved with the continued reliance on current livestock systems which depend on land conversion and over-exploitation of grassland and forage resources to meet current demands for livestock products. The failure of this approach is evident in the declining health of the world's grassland through reduced productivity, loss of biodiversity, increased soil erosion, reduced water yield and quality and high GHG emissions. The magnitude of many of these symptoms are greater in developing countries where the majority of livestock are tended by smallholders struggling to survive using traditional systems with limited support to facilitate change.

To achieve sustainability requires the twin aims of increasing livestock production and reducing environmental impacts (Charles *et al.* 2015).Sustainable intensification is a means to achieve 'win-win' outcomes for grasslands, the environment and smallholder. We agree with Garnett (2014) that smallholder production systems can be refashioned with reduced livestock number to deliver better nutritional outcomes with more efficient production using the same forage resources but at lower environmental costs and increased income for low income farm households. The constraints to achieving sustainability across the livestock sector are not technical, but are sociological, economic and political.

References

ABARES, 2013.*Agricultural commodities September quarter 2013*, Australian Bureau of Agricultural and Resource Economics and Sciences, Canberra

ABS, 1982.Year Book Australia, 1982 (1301.0) Australian Bureau of Statistics, Australian Government, Canberra.

Alexandratos, N. and J. Bruinsma. 2012. World Agriculture towards 2030/2050: The 2012 Revision. Food and Agriculture Organization of the United Nations, Rome

Alkemade, R., R. S. Reid, M. van den Berg, J. de Leeuw and M. Jeuken. 2013. Assessing the impacts of livestock production on biodiversity in rangeland ecosystems. *Philosophical Transactions of the Royal Society.***110:** 20900-20905

Allen, V. G., C. Batello, E.J. Berretta, J. Hodgson, M. Kothmann, X. Li, J. McIvor, J. Milne, C. Morris, A. Peeters and M. Sanderson. 2011. An international terminology for grazing lands and grazing animals. *Grass and Forage Science* **66:** 2–28

Allievi, F., M. Vinnari and J. Luukkanen. 2015. Meat consumption and production - analysis of efficiency, sufficiency and consistency of global trends, *Journal of Cleaner Production* **92:** 142-151

Archibold, O. W. 1995. Ecology of world vegetation.Chapman and Hall.London/New York.

Blair, John, Jesse Nippert and John Briggs. 2014. Chapter 14: Grassland Ecology. pp. 389-423. In: R. K. Monson (Ed.) *Ecology and the Environment*, Springer Science+Business Media New York, USA

Ayalew, W., J. M. King, E. Burns and B. Rischkowsky. 2003. Economic evaluation of smallholder subsistence livestock production: lessons from an Ethiopian goat development program. *Ecological Economics* **45:** 473-485

Badgery, W, D. Michalk and D. Kemp. 2015. Sustainable management of temperate grasslands in Australia. In 'World Grasslands: Opportunities and Challenges'. *See special volume produced for 23rd International Grassland Congress, India November 2015*

Bell, A.K. and C.J. Allan. 2000. PROGRAZE – an extension package in grazing and pasture management. *Australian Journal of Experimental Agriculture* **40:** 325–330

Bajželj, B., K. S. Richards, J. M. Allwood, P. Smith, J. S. Dennis, E. Curmi and C. A. Gilligan. 2014. Importance of food-demand management for climate mitigation. *Nature Climate Change* **4:** 924-929.

Bridle, K.L. and R. J. Price. 2011.**Undertaking participatory research at a national scale: the Biodiversity in Grain & Graze approach.** *Animal Production Science* **49:** 916–927

Briske, D. D., M. Zhao, G. Han, C. Xiu, D. R. Kemp, W. Willms, K. Havstad, L. Kang, Z. Wang, J. Wu, X. and Y. Bai. 2015. Strategies to alleviate poverty and grassland degradation in Inner Mongolia: intensification vs production efficiency of livestock systems. *Journal of Environment Management* **152:** 177-82

Brookshire, E. N. J. and T. Weaver. 2015. Long-term decline in grassland productivity driven by increasing dryness. *Nature Communications*. 6: 7148, DOI: 10.1038/ncomms8148

Burney, J.A., S. J. Davis and D. B. Lobell.2010. Greenhouse gas mitigation by agricultural intensification. *Proceedings of the National Academy of Sciences of the United States of America*, **107:** 12052–12057

Caro, D., S. J. Davis, S. Bastianoni and K. Caldeira. 2014. Global and regional trends in greenhouse gas emissions from livestock. *Climatic Change* **126:** 203–216

Charles, H., J. Godfray and T. Garnett. 2015. Food security and sustainable intensification. *Philosophical Transactions of the Royal Society B*.**369:** 20120273.

Clay, D. E., S. A. Clay, K. D. Reitsma, B. H. Dunn, A. J. Smart, G. G. Carlson, D. Horvath and J. J. Stone. 2014. Does the conversion of grasslands to row crop production in semi-arid areas threaten global food supplies? Global Food Security **3:** 2–30

Conant, R.T. 2010. Challenges and opportunities for carbon sequestration in grassland systems: A technical report on grassland management and climate change mitigation.*Integrated Crop Management* 9: Plant Production and Protection Division, Food and Agriculture Organization of the United Nations, Rome

Fan, J., H. Zhong, W. Harris, G. Yu, S. Wang, Z. Hu and Y. Yue. 2009. Carbon storage in the grasslands of China based on field measurements of above- and below-ground biomass. *Climate Change* **86:** 375–396

Foley, J. A, N. Ramankutty, K. A. Brauman, E. S. Cassidy, J. S. Gerber, M. Johnston, N. D. Mueller, C. O'Connell, D. K. Ray, P. C. West, C. Balzer, E. M. Bennett, S. R. Carpenter, J. Hill, C. Monfreda, S. Polasky, J. Rockström, J. Sheehan, S. Siebert, D. Tilman and D. P. Zaks. 2011. Solutions for a cultivated planet. *Nature* **Volume: 478**: Pages:337–342

FAO. 2006a. *Livestock's Long Shadow. Environmental Issues and Options* (Rome, Italy: Food and Agriculture Organization of the United Nations, Rome

FAO. 2006b. Livestock report 2006. Food and Agriculture Organization of the United Nations, Rome

FAO. 2007. The state of the world's genetic resources for food and agriculture. Food and Agriculture Organization of the United Nations, Rome

FAO.2013a. *World Livestock 2013 – Changing disease landscapes.* United Nations Food and Agriculture Organisation, Rome

FAO.2013b. Current worldwide annual meat production in tonnes per country (Livestock and fish primary equivalent).Food and Agriculture Organization of the United Nations, Rome

FAO. 2014a. *Building a common vision for sustainable food and agriculture: Principles and Approaches.*United Nations Food and Agriculture Organisation, Rome

FAO. 2014b. Food Outlook: Biannual report on global food markets. Food and Agriculture Organisation of the United Nations, Rome, October, 2014

FAOSTAT. 2014. FAO Statistical database. Food and Agriculture Organisation of the United Nations, Rome.

Franklin, K. A., K. Lyons, P. L. Nagler, D. Lampkin, E. P. Glenn, F. Molina-Freaner, T. Markow and A. R. Huete. 2006. Buffelgrass (*Pennisetumciliare*) land conversion and productivity in the plains of Sonora, Mexico. *Biological Conservation* **127:** 62-71

Gang, C. C., W. Zhou, Y. Z. Chen, Z. Q. Wang, Z. G. Sun, J. L. Li, J. G. Qi and I. Odeh. 2014. Quantitative assessment of the contributions of climate change and human activities on global grassland degradation. *Environmental Earth Science* **72:** 4273–4282

Garnett, T. 2011. Where are the best opportunities for reducing greenhouse gas emissions in the food system (including the food chain)? *Food Policy* **36:** S23-S32

Garnett, T. 2014. Three perspectives on sustainable food security: efficiency, demand restraint, food system transformation. What role for life cycle assessment? *Journal of Cleaner Production* **73:** 10-18

Gavier-Pizarro, G.I., N. C. Calamari, J. J. Thompson, S. B. Canavelli, L. M. Solari, J. Decarre, A. P. Goijman, R. P. Suarez, J. N. Bernardos and M. E. Zaccagnini. 2012. Expansion and intensification of row crop agriculture in the Pampas and Espinal of Argentina can reduce ecosystem service provision by changing avian density. *Agriculture, Ecosystems and Environment* **154:** 44–55

Gerber, P.J., B. Henderson, C. Opio, A. Mottet and H. Steinfeld.2013. Tackling climate change through livestock — A global assessment of emissions and mitigation opportunities. Food and Agriculture of the United Nations, Rome.

Gerosa, S. and J. Skoet. 2012. Milk availability: Trends in production and demand and medium-term outlook. ESA Working paper No. 12-01, Agricultural Development Economics Division, Food and Agriculture Organisation of the United Nations, Rome

Ghahramani, A. and A.D. Moore. 2015. Systemic adaptations to climate change in southern Australian grasslands and livestock: Production, profitability, methane emission and ecosystem function. *Agricultural Systems***133:** 158-166.

Haregeweyn, N., J. Poesen, G. Verstraeten, G. Govers, J. de Vente, J. Nyssen, J. Deckers and J. Moeyersons,J. 2013. Assessing the performance of a spatially distributed soil erosion and sediment delivery model (WATEM/SEDEM in Northern Ethiopia.*Land Degradation & Development* **24:** 188- 204

Havlík, P., H. Valin, M. Herrero, M. Obersteiner, E. Schmid, M. C. Rufino, A. Mosnier, P. K. Thornton, H. Böttcher, R. T. Conant, S. Frank, S. Fritz, S. Fussa, F. Kraxner and A. Notenbaert. 2014. Climate change mitigation through livestock system transitions. *Proceedings of the National Academy of Sciences of the United States of America* **111:** 3709-3714

Heinrich Böll Foundation.2014. Meat Atlas: Facts and figures about the animals we eat. Heinrich Böll Foundation, Schumannstr. 8, 10117 Berlin, Germany

Henchion, M., M. McCarthy, V. C. Resconi and D. Troy. 2014. Meat consumption: Trends and quality matters. *Meat Science* **98:** 561-568

Henderson, B., A. Falcucci, A. Mottet, L. Early, B. Werner, H. Steinfeld and P. Gerber.2015a. Marginal costs of abating greenhouse gases in the global ruminant livestock sector.*Mitigation and Adaptation Strategies for Global Change* 1-26

Henderson, B.B., P. J. Gerber, T. E. Hilinski, A. Falcucci, D. S. Ojima, M. Salvatore and R. T. Conant. 2015b. Greenhouse gas mitigation potential of the world's grazing lands: modelling soil carbon and nitrogen fluxes of mitigation practices. *Agriculture Ecosystems and Environment* **207:** 91–100

Hemme, T. and J. Otte. 2010. Status and prospects for smallholder milk production: A Global perspective. Food and Agriculture Organisation of the United Nations. Rome. p. 186

Herrero, M. and P. K. Thornton. 2013. Livestock and global change: Emerging issues for sustainable food systems.*Proceedings of the National Academy of Sciences of the United States of America* **110:**20878–20881

Herrero, M., P. Havlík, H. Valin, A. Notenbaert, M. C. Rufino, P. K. Thornton, M. Blümmel, F. Weisc, D. Grace and M. Obersteiner. 2013a. Biomass use, production, feed efficiencies and greenhouse gas emissions from global livestock systems. *Proceedings of the National Academy of Sciences of the United States of America* **110:**20888–20893

Herrero, M., D. Grace, J. Njuki, N. Johnson, D. Enahoro, S. Silvestri and M. Rufino. 2013b. The roles of livestock in developing countries. *Animal***7(S 1):** 3–18

Hilker, T., E. Natsagdorj, R. H. Waring, A. Lyapustin and Y. J. Wang. 2014. Satellite observed widespread decline in Mongolian grasslands largely due to overgrazing. *Global Change Biology* **20:** 418-428

Hoffmann, I. 2011. Livestock biodiversity and sustainability.*Livestock Science* **139:** 69–79

Huber, J. 2000. Towards industrial ecology: sustainable development as a concept of ecological modernization. *Journal of Environmental Policy and Planning* **2:** 269-285

Hughes, J., I. J. Packer, D. L. Michalk, P. M. Dowling, W. McG. King, S. Brisbane, G. D. Millar and S. M. Priest. 2006. Sustainable grazing systems for the Central Tablelands of NSW. 4. Soil water dynamics and runoff events for differently grazed pastures at Carcoar. *Australian Journal of Experimental Agriculture* **46:** 483-494

ILRI. 1999. Economic valuation of animal genetic resources. Proceedings of an FAO:ILRI workshop held at FAO Headquarters, Rome, Italy, 15–17 March, International Livestock Research Institute, Nairobi, Kenya, p. 80.

Jackson, L.E., T. Rosenstock, M. Thomas, J. Wright, A. Symstad. 2009. Managed ecosystems: biodiversity and ecosystem functions in landscapes modified byhuman use. In: Naeem, S., Bunker, D., Hector, A., Loreau, M., Perrings, C. (Eds.) Biodiversity and Human Impacts. Oxford University Press, Oxford, UK, pp. 178–194 (Chapter 13)

Johnson, J.A., C. F. Runge, B. Senauer, J. Foley and S. Polasky. 2014. Global agriculture and carbon trade-offs. *Proceedings of the National Academy of Sciences of the United States of America* **111:** 12342-12347

Jones, R.J. and R.L. Sandland. 1974. The relation between animal gain and stocking rate: derivation of the relation from the results of grazing trials. *Journal of Agricultural Science, Cambridge* **83:** 335-342

Joyce, J. and J. P. Morgan. 1989. Manitoba's tall-grass prairie conservation project. Prairie pioneers: ecology, history and culture. August, 1988. *Proceeding of the Eleventh North American Prairie Conference*, held August 7-11, 1988. Edited by Bragg, T.B. and Stubberndieck, J. University of Nebraska Printing. Lincoln, NE

Kemp, D.R. and P.M. Dowling. 2000. Towards sustainable temperate perennial pastures. *Australian Journal of Experimental Agriculture* **40:** 125-132

Kemp, D. R. and D. L. Michalk. 2007. Towards sustainable grassland and livestock management. *Journal of Agricultural Science* **145:** 543-564

Kemp, D.R., and Michalk, D.L. (Eds).(2011). *Sustainable Development of Livestock Systems on Grasslands in North-Western China*.ACIAR Proceedings 134.*pp* 189

Kemp, D.R., D.L. Michalk, J.M. Virgona. 2000. Towards more sustainable pastures: lessons learnt. *Australian Journal of Experimental Agriculture* **40:** 343-356

Kemp, D. R., W. B. Badgery and D. L. Michalk. 2015a. Sustainable grasslands: resolving management options for livelihood and environmental benefits.*Proceedings of the XXIII International Grassland Congress*, New Delhi, India

Kemp D.R., W.B. Badgery and D.L. Michalk. 2015b. Principles for grassland systems research for livelihoods and environmental benefits. *See special volume produced for 23rd International Grassland Congress, India November 2015*

Kemp, D.R., King, W.McG., Lodge, G.M., Murphy, S.R., Quigley, P., and Sanford, P. (2003). SGS Biodiversity Theme: The impact of plant biodiversity on the productivity and stability of grazing systems. *Australian Journal of Experimental Agriculture* **43**: 962-975

Kemp, D. R., G. D. Han, X. Y. Hou, D. L. Michalk, F. J. Hou, J. P. Wu and Y. J. Zhang. 2013. Innovative grassland management systems for environmental and livelihood benefits. *Proceedings of the National Academy of Sciences of the United States of America* **110:** 8369-8374

Landis, D.A. and B. P. Weling. 2010. Arthropods and biofuel production systems in North America. *Insect Science* **17:** 220–236

Lavorel, S. and K. Grigulis. 2012. How fundamental plant functional trait relationships scale-up to trade-offs and synergies in ecosystem services? *Journal of Ecology* **100:** 128–140

Lee M., P. Manning, J. Rist, S. A. Power and C. Marsh. 2010. A global comparison of grassland biomass responses to CO2 and nitrogen enrichment. *Philosophical Transactions of the Royal Society B* **365:** 2047–2056

Liu Y.G. 1998. Institutional and policy reform of rural extension in China during the transition towards a market economy. In 'Training for agricultural and rural development 1997–1998 issue'. Food and Agriculture Organization of the United Nations: Rome

Maeda, E.E., P. K. E. Pellikka, M. Siljander and B. J. F. Clark. 2010. Potential impacts of agricultural expansion and climate change on soil erosion in the Eastern Arc Mountains of Kenya. *Geomorphology* **123:** 279–289

Mason, W.K., G.M. Lodge, C.J. Allan, M.H. Andrew, T. Johnson, B. Russell, I.H. Simpson. 2003. An appraisal of Sustainable Grazing Systems: the program, the triple bottom line impacts and the sustainability of grazing systems. *Australian Journal of Experimental Agriculture* **43:** 1061-1082

McDermott, J.J., S. J. Staal, H. A. Freeman, M. Herrero and J. A. Van de Steeg. 2010. Sustaining intensification of smallholder livestock systems in the tropics. Livestock Science **130:** 95–109

McIvor JG, Williams J, Gardener CJ (1995) Pasture management influences runoff and soil movement in the semiarid tropics. *Australian Journal of Experimental Agriculture* **35:** 55-65

McTainsh, G.H., J.F. Leys, T. O'Loingsigh, C.L. Strong. 2011. Wind erosion and land management in Australia during 1940-1949 and 2000-2009. *Report prepared for the Australian Government Department of Sustainability, Environment, Water, Population and Communities on behalf of the State of the Environment 2011 Committee. DSEWPaC, Canberra*

Millennium Ecosystem Assessment. 2005. *Ecosystems and Human Well-being: Synthesis*. Island Press, Washington, DC

Michalk, D., Wu Jian Ping, W. Badgery and D. Kemp. 2015. Impact of market forces on product quality and grassland condition. *Proceedings of the XXIII International Grassland Congress*, New Delhi, India

MLA. 2015. Australia's sheepmeat industry. Fast Facts 20914. Meat & Livestock Australia Limited, February 2015.

National Land and Water Resources Audit.2001. Australian dryland salinity assessment 2000. Commonwealth of Australia, Canberra: NLWRA

OECD/FAO (2014) *OECD-FAO Agricultural Outlook 2014*, OECD Publishing, Paris

O'Mara, F. P. 2012. The role of grasslands in food security and climate change.*Annals of Botany***110:** 1263-1270.

Qiu, H. G., J. K. Huang, J. Yang, S. Rozelle, Y. H. Zhang, Y. H. Zhang and Y. L. Zhang. 2010. Bioethanol development in China and the potential impacts on its agricultural economy. *Applied Energy* **87:** 76–83

Olofsson, J. and T. Hickler. 2008.Effects of human land-use on the global carbon cycle during the last 6,000 years. *Vegetation History and Archaeobotany* **17:** 605-615

Ontario Ministry of Natural Resources.2009. Natural Heritage Information Center (NHIC) database.Ontario Ministry of Natural Resources. Peterborough, ON, Canada

Petz, K., R. Alkemade, M. Bakkenes, C. J. E. Schulp, M. van der Velde and R. Leemans. 2014. Mapping and modelling trade-offs and synergies between grazing intensity and ecosystem services in rangelands using global-scale datasets and models. *Global Environmental Change* 29: 223–234

Raghuvanshi, G. and Y. Singh.2015. Agriculture biotechnology for sustainable food security: A review *Indian Research Journal of Genetics and Biotechnology* **7:** 311 – 319

Ripple, W. J., P. Smith, H. Haberl, S. A. Montzka, C. McAlpine and D. H. Boucher. 2014. Ruminants, climate change and climate policy. *Nature Climate Change* **4:** 1-3

Robertson, K.R., R. C. Anderson and M. W. Schwartz. 1997. The tallgrass prairie mosaic. *In:* Conservation *in*highly fragmented landscapes. Edited by Schwartz, M.W. Chapman and Hall. New York, NY. pp. 55-87

Samson, F.B., F. L. Knopf and W. R, Ostlie. 2004. Great Plains ecosystems: past, present and future. *Wildlife Society Bulletin* **32:** 6-15

Sanjari, G., B. F. Yu, H. Ghadiri, C. A. A. Ciesiolka and C. W. Rose. 2009.Effects of time-controlled grazing on runoff and sediment loss. *Australian Journal of Soil Research* **47:** 1-13

Scherr S.J. and S. Yadav. 1996.Land Degradation in the Developing World: Issues and Policy Options for 2020. In: The Unfinished Agenda - Perspectives on Overcoming Hunger, Poverty and Environmental Degradation (IFPRI, 2001, 314 p.)

Shevliakova, E., S. W. Pacala, S. Malyshev, G. C. Hurtt, P. C. D. Milly, J. P. Caspersen, L. T. Sentman, J. P. Fisk, C. Wirth and C. Crevoisier. 2009. Carbon cycling under 300 years of land use change: Importance of the secondary vegetation sink. *Global Biogeochemical Cycles* **23:** 1-16

Sirohi, S. 2015. Opportunities and challenges for carbon trading from livestock sector. pp. 239-252. In: V. Sejian, J., J. Gaughan, L. Baumgard and C. Prasad (Editors) Climate Change Impact on Livestock: Adaptation and Mitigation.Springer India

Smith, P., D. Martino, Z. Cai, D. Gwary, H. Janzen, P. Kumar, B. McCarl, S. Ogle, F. O'Mara, C. Rice, B. Scholes, O. Sirotenko, 2007. Agriculture. In Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Smith, P., H. Haberl, A. Popp, K-H.Erb, Christian Lauk, R. Harper, F. N. Tubiello, A. de Siqueira Pinto, M. Jafari, S. Sohi, O. Masera, H. Böttcher, G. Berndes, M. Bustamante, H. Ahammad, H. Clark, H. M. Dong, E. A. Elsiddig, C. Mbow, N. H. Ravindranath, C.W. Rice, C. Robledo Abad, A. Romanovskaya, F. Sperling, M. Herrero, J. I. House and S. Rose. 2013. How much land based greenhouse gas mitigation can be achieved without compromising food security and environmental goals? *Global Change Biology* **19:** 2285–2302

Soussana, J.-F., K. Klumpp and F. Ehrhardt. 2014. The role of grassland in mitigating climate change. pp. 76-87. In: A. Hopkins, R. P. Collins, M. D. Fraser, V. R. King, D. C. Lloyd, J. M. Moorby and P. R. H. Robson (Editors) The Future of European Grasslands. Proceedings of the 25th General Meeting of the European Grassland Federation, Aberystwyth, Wales 7-11 September 2014.

St Clair, S. B., E. A. Sudderth, M. L. Fischer, M. S. Torn, S. A. Stuart, R. Salve, D. L. Eggett and D. D. Ackerly. 2009 Soil drying and nitrogen availability modulate carbon and water exchange over a range of annual precipitation totals and grassland vegetation types. *Global Change Biology* **15:** 3018–3030

Stoll-Kleemann, S. and T. O'Riordan. 2015. The sustainability challenges of our meat and dairy diets, *Environment: Science and Policy for Sustainable Development* **57:** 34-48

Suttie, J.M., S. G. Reynolds and C. Batello (editors). 2005. Grasslands of the World. *Food and Agriculture Organization of the United Nations, Plant Production and Protection Series No 34*.Food and Agriculture Organization, Rome, Italy

Thornton, P.K. 2010.Livestock production: recent trends, future prospects. *Philosophical Transactions of the Royal Society B* **365:** 2853–2867

Thornton, P. K. and M. Herrero. 2010. Potential for reduced methane and carbon dioxide emissions from livestock and pasture management in the tropics. *Proceedings of the National Academy of Sciences of the United States of America* **107:** 19667-19672

Thornton, P., M. Herrero and P. Ericksen. 2011. Livestock and climate change. *Livestock Exchange Issue Brief 3*, November 2011. International Livestock Research Institute, Nairobi, Kenya

Tilman, D., C. Balzer, J. Hill and B. L. Befort. 2011. Global food demand and the sustainable intensification of agriculture. *Proceedings of the National Academy of Science of the United States of America***108:** 20260–20264.

Töpfer, K., J. D. Wolfensohn and J. Lash. 2000. People and Ecosystems: The Fraying Web of Life. **World Resources 2000-2001.** World Resources Institute, Washington DC

Tscharntke, T., A. M. Klein, A. Kruess, I. Steffandewenter and C. Thies. 2005. Landscape perspectives on agricultural intensification and biodiversity – ecosystem service management. *Ecology Letters* **8:** 857–874

Tscharntke, T., Y. Clough, T. C. Wanger,, L. Jackson, I. Motzke, I. Perfecto, J. Vandermeer and A. Whitbread. 2012. Global food security, biodiversity conservation and the future of agricultural intensification. *Biological Conservation* **151:** 53–59.

Tubiello, F. N., M. Salvatore, S. Rossi, A. Ferrara, N. Fitton and P. Smith. 2013. The FAOSTAT database of greenhouse gas emissions from agriculture. *Environmental Research Letters* **8:** 1–10

UN. 1987. Our Common Future. Report of the World Commission on Environment and Development, World Commission on Environment and Development, 1987. Published as Annex to General Assembly document A/ 42/427, Development and International Co-operation: Environment August 2, 1987

Vitousek, P.M. and D.U. Hooper. 1993. Biological diversity and terrestrial ecosystem biogeochemistry. pp. 3-14. In:E.-D. Schulze and H.A. Mooney, editors.*Biodiversity and Ecosystem Function*. Springer-Verlag, Berlin, Germany.

Weindl, I., H. Lotze-Campen, A. Popp, C. Müller, P. Havlík, M. Herrero, C. Schmitz and S. Rolinski. 2015. Livestock in a changing climate: production system transitions as an adaptation strategy for agriculture. *Environmental Research Letters* **10:** 094021

Westhoek, H., T. Rood, M.v.d. Berg, J. Janse, D. Nijdam, M.A. Reudink and E. Stehfest. 2011. The protein puzzle: the consumption and production of meat, dairy and fish in the European Union. PBL (Netherlands Environmental Assessment Agency) The Hague/Bilthoven

Westcott, P. and J. Hansen. 2015. USDA Agricultural Projections to 2024. USDA Agricultural Projections No. (OCE-151) 97 pp, February 2015

White, R., S. Murray and M. Rohweder. 2000. Pilot analysis of global ecosystems (PAGE): grassland ecosystems. World Resources Institute (WRI) Washington, DC, USA.

Wiebe, B. H., R. G. Eilers, W. G.Eilers and T. Brierley.2005. Development of a risk indicator for dryland salinization on the Canadian Prairies. *Proceedings of the International Salinity Forum*, Riverside, California, April 2005, 473–476

Wilson, J. B., R. K. Peet, J. Dengler and M. Pärtel.2012. Plant species richness: the world records. *Journal of Vegetation Science* **23:** 769-802

Wolf, J., T. O. West, Y. L. Le Page, G. P. Kyle, X. S. Zhang, G. J. Collatz, M. L. Imhoff. 2015. Biogenic carbon fluxes from global agricultural production and consumption. *Global Biogeochemical Cycles*.doi: 10.1002/2015GB005119

World Bank. 2007. Agriculture for development. World Development Report, 2008.World Bank, Washington DC.

Wu, J. P., D. Michalk, D. Kemp, L. Yang and X. Y. Gong. 2011. Talking with China's livestock herders: what was learnt about their attitudes to new practices. pp. 162–176. In: Kemp D.R. and Michalk D.L. (eds) 2011. Development of sustainable livestock systems on grasslands in north-western China.ACIAR Proceedings No. 134. Australian Centre for International Agricultural Research: Canberra

Zhou, Z. Y., W. M. Tian, J. M. Wang, H. B Liu and L. J. Cao. 2012. Food Consumption Trends in China.April 2012. Report submitted to the Australian Government Department of Agriculture, Fisheries and Forestry, Canberra, Australia

Zulauf, C. 2015.China, India, the food transition and future demand growth.*farmdoc daily* **5:**122, Department of Agricultural and Consumer Economics, University of Illinois at Urbana-Champaign, July 2, 2015

Contributors

D.R. Kemp

Charles Sturt University, Graham Centre for Agricultural Innovation, Orange NSW Australia 2800 E:

W.B. Badgery

Orange Agricultural Institute, NSW Department of Primary Industries, Orange NSW Australia 2800

Wu Jianping

China Agricultural University, Beijing 100094, People's Republic of China.

Zhang Yinjun

Gansu Agricultural University, Lanzhou, Gansu Province, Peoples Republic of China.

P.J. Thomassin

Department of Agricultural Economics, McGill University, Macdonald Campus, Quebec, Canada