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Sustainability and future food security—A global perspective for livestock production

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Abstract

Grasslands are the predominant forage source for grazing animals and cover more of the Earth's land than any other major vegetation type. Their values are not always recognised, and conversion to other uses is continuing at a high rate leading to greater environmental and socio-economic problems. Overgrazing is one of the main drivers of productivity decline of grasslands, 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. Biodiversity and greenhouse gas production have also been particular concerns. Estimates of productivity change all show a decline over recent decades, yet animal numbers continue to increase, particularly in the developing world. This paper critically reviews the projected demands for livestock products, driven largely by human population growth; the current health of the world's grasslands and how current livestock systems that depend on land conversion and overexploitation of grassland are inappropriate and need to be improved. Central to this argument is that small holders in the developing world will be responsible for a large amount of the future red meat production, and this can be achieved through more efficient livestock production systems using lower stocking rates. The Australian sheep industry is provided as an example of how livestock production and reduced environmental impacts can be achieved with improved efficiency. Changes will require smallholders to transition to a competitive, market-oriented livestock industry, which will provide challenges.

KEYWORDS

efficiency, grassland degradation, livestock productivity, overgrazing, sustainable development

1 | INTRODUCTION

By 2050, the agricultural sector will face the challenge of producing 60% more than the current food, feed, and fibre supply of 8.5 billion t/year to sustain a global population forecast to be 9.3 billion people (FAO, 2014a) while preserving essential ecosystem processes that underpin our sustainable future. To meet this challenge, 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 increased global agricultural production more than threefold over a 50-year period with only 12% expansion in the area of land farmed (FAO, 2014a). This Green Revolution, which increased yields, not only allowed farmers to improve food availability at affordable prices but also saved millions of hectares of grasslands and forests from conversion to cropping land; it prevented the loss of an immeasurable amount of ecosystem services and circumvented an estimated 590 billion tonnes of carbon dioxide (CO_2) emissions into the atmosphere (Burney, Davis, & Lobell, 2010).

Recent forecasts estimate that intensification will result in 80% of the future increase in agricultural production globally with extensification accounting for 20% (Alexandratos & Bruinsma, 2012). Closing 'yield gaps' on underperforming lands to double food supply and greatly reduce the environmental impacts of agriculture will be needed to halt the expansion of cropping into forests, grasslands, and wetlands (Foley et al., 2011). In practice, however, political instability, lack of infrastructure, and incapability of poor farmers to finance essential inputs and equipment all constrain the potential for intensification in current low-yield regions (Johnson, Runge, Senauer, Foley, & Polasky, 2014).

At the same time, the shift from cereals as staples to protein-rich diets (FAO, 2013) is increasing demand for red meat, which is predicted to more than double during the next 20 years (Thornton, 2010). This provides opportunities for grass-based ruminant producers, especially the 1 billion smallholders in the developing world, to use their livestock enterprises as a way out of poverty (McDermott, Staal, Freeman, Herrero, & Van de Steeg, 2010) and improve global food security (Herrero & Thornton, 2013). However, achieving sustainable livestock production, particularly for smallholders, will require actions to efficiently increase productivity to improve rural livelihoods and social well-being; conserve, protect, and enhance natural ecosystems; and improve systems of governance (FAO, 2014a; Godfray & Garnett, 2015). In this review, we will focus on one of the challenges of sustainability, namely, the potential for a significant and sustainable increase in production by improving livestock productivity using resources more efficiently.

We do this by analysing the demand–supply interactions in the global livestock sector to identify the drivers that influence the potential to redesigning systems to efficiently meet growing demands for animal products and avoid further environmental change. 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, and 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.

2 | GLOBAL MEAT AND MILK PRODUCTION AND CONSUMPTION: TRENDS AND CHALLENGES

Worldwide meat production has almost quadrupled from 78 to 331 Mt, between 1963 and 2015. About 25% is derived from cattle, sheep, and goats (FAO, 2014b; Figure 1). The OECD/FAO (2014) forecast that global meat production will increase 19% by 2023 and that developing countries will supply 78% of the additional 57 Mt produced, much of this demand being driven by increasing household incomes. Almost all of the predicted increase in red meat (beef, sheep, and goat) 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% of all beef exports, is expected to continue to grow. By 2030, global meat production is predicted to exceed 455 Mt with increasing

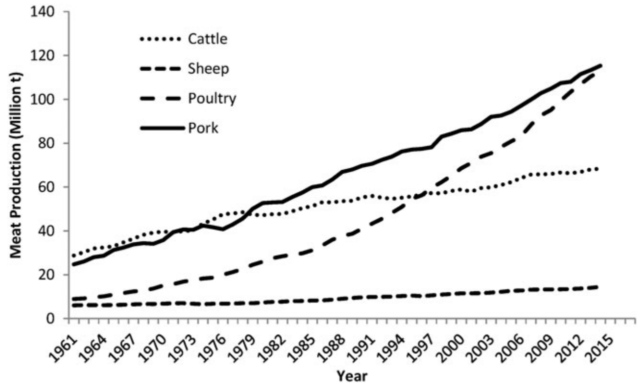

FIGURE 1 World meat production of cattle (including buffalo), sheep (including goats), poultry, and pork from 1961 to 2014 (Million t; FAOSTAT data)

contributions from developing countries (Alexandratos & Bruinsma, 2012).

Between 1963 and 2015, milk production has more than doubled from 340 to 818 Mt (Gerosa & 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. In India, for example, milk production has increased nearly sixfold (21–117 Mt) since 1970, making it the world's leading milk producer (FAO, 2006b). On the demand side, milk consumption grew by an average of 3–4% per year (1995–2005) in South Asia, doubling the growth rates recorded for staple foods (Hemme & 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.

3 | GLOBAL GRASSLAND AND FORAGE RESOURCES: DISTRIBUTION, STATUS, USE, AND THREATS

Grasslands are the predominant forage source for grazing animals, cover more of the Earth's land than any other major vegetation type, and are important to sustain human societies by providing critical ecosystem goods (products from cattle, sheep, goats, and camels), wildlife habitat, and services (climate change regulation, genetic resources, erosion control, water provision, air purification, and cultural and amenity services) at various scales. The continued health of these ecosystems depends in turn on how they are used and managed. However, due to overgrazing by livestock, extensive clearing for crop production, and urban expansion, many grassland communities are now among the world's most endangered ecosystems (Blair, Nippert, & Briggs, 2014).

3.1 | Defining grassland resources

Grassland resources are very diverse and difficult to define (Blair et al., 2014) because the term 'grassland' has evolved to cover 'all land committed to a forage use' including pastureland, forestland, cropland, and rangeland (Allen et al., 2011). Grassland vegetation comprises grasses, legumes, other forbs, and woody species that may be indigenous or exotic and may occur as monocultures (forage crop), mixtures of two or more species (sown pasture), or rich and diverse natural plant communities (Blair et al., 2014). Grasslands range from temporary sown pastures integrated as leys in crop rotation systems to permanent natural ecosystems used for grazing by livestock and wildlife, for example, savannahs of Africa; grasslands of Australia; 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 rare and are often only found as remnant reserves that need to be managed to prevent reversion to forests (Tscharntke, Klein, Kruess, Steffandewenter, & Thies, 2005). A critical step to improve the way grassland ecosystems are managed is to audit their extent, monitor their condition, and assess their capacity to provide the goods and services the world needs (White, Murray, & Rohweder, 2000).

3.2 | Distribution of grassland ecosystems

The global distribution of the approximately 54 M km^2 of grasslands (approximately 40% of the world's land area; White et al., 2000) extends to all ice-free latitudes (Figure 2) and in altitude ranging from coastal to montane regions at elevations above 4,000 m. Other estimates have been lower at 28 M km^2 (Ramankutty, Evan, Monfreda, & Foley, 2008), primarily due to the indefinite division between woodlands and shrubby savannah. Grasslands cover a range of climates from temperate to tropical with annual rainfall extending from below 250 mm/year in arid grasslands to above 1,000 mm/year in mesic grasslands. Average annual temperatures vary from 0°C to above 25°C. Soil factors, seasonality of precipitation, grazing, and fire are also important factors in determining local vegetation structure and composition.

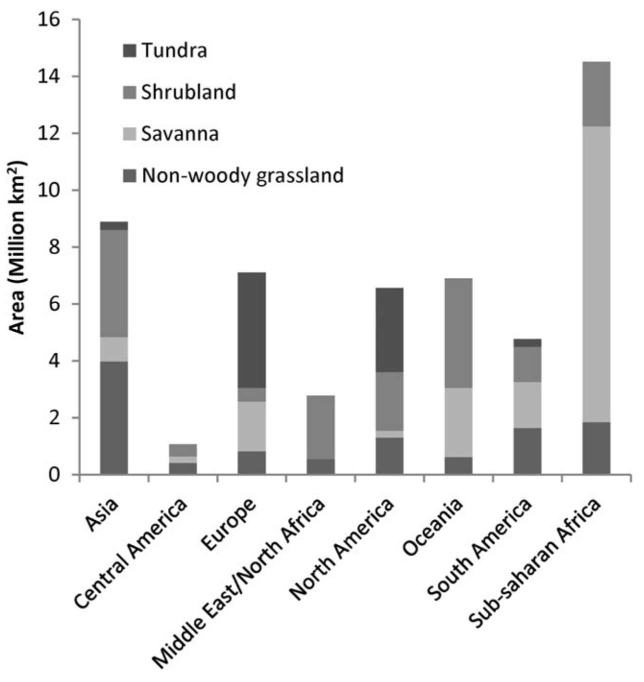

FIGURE 2 Area (Million km^2) of grasslands biomes in regions of the world (adapted from White et al., 2000)

This wide climatic and topographic range makes grasslands very diverse ecosystems. Sub-Saharan Africa and Asia have the largest total grassland area, 14.5 and 8.9 M km^2, respectively (Figure 2). Five countries (Australia, the Russian Federation, China, the United States, and Canada) each have more than 3 M km^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 M km^2 of grassland (Mongolia, Kazakhstan, Angola, South Africa, and Ethiopia).

3.3 | Loss of grassland ecosystems through conversion to cropping

Although this review is mostly focused on the impacts of grazing and its interaction with the environment, we acknowledge that conversion to croplands has been the main cause of the loss of grasslands globally. Temperate grasslands with better soils and more frequent rainfall had been mostly cleared for crops by the 1950s (Millennium Ecosystem Assessment, 2005), whereas poorer quality semiarid grasslands were left for grazing livestock (Suttie, Reynolds, & Batello, 2005). This means that the current and future threats to grassland ecosystems are high due to rapidly expanding agricultural sectors in South America (Gavier-Pizarro et al., 2012), southern Africa (Maeda, Pellikka, Siljander, & Clark, 2010), North America (Landis & Weling, 2010), and Asia (Foley et al., 2011; Qiu et al., 2010).

Conversion of land to cropping, mixed farming, and sown pastures has affected some 33 M km^2, 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, Wolfensohn, & Lash, 2000). To date, the loss through conversion has been greatest in developed countries. For example, by 2003, the United States had lost over 97% of tallgrass prairie, 71% of mixed prairie, and 48% of shortgrass prairie (Robertson, Anderson, & Schwartz, 1997; Samson, Knopf, & Ostlie, 2004).

The Millennium Ecosystem Assessment (2005) scenarios predict that a further 10–20% of grassland and forest resources will be converted, primarily to cropland before 2050, mostly concentrated in dry and tropical regions in developing countries (Figure 3). A small increase in forest cover is predicted for developed countries as part of greenhouse gas (GHG) abatement programmes.

3.4 | Current state of grazed grasslands

Indicators used to determine change in grassland condition include shift in species composition, loss of biodiversity, reduced biomass production and plant cover, low small ruminant productivity, erosion and changed soil properties evident in loss of soil carbon, acidification, and reduced water infiltration. The first signs of change in grassland condition due to overgrazing are species shifts and reduced production and with typically the more palatable perennial grasses being replaced by less palatable species, for example, shrubs and forbs (Liang et al., 2009; Zhang et al., 2015). Overall, the condition of the world's grassland resources is far from satisfactory (Suttie et al., 2005) with degradation evident in all grassland types caused mostly by using

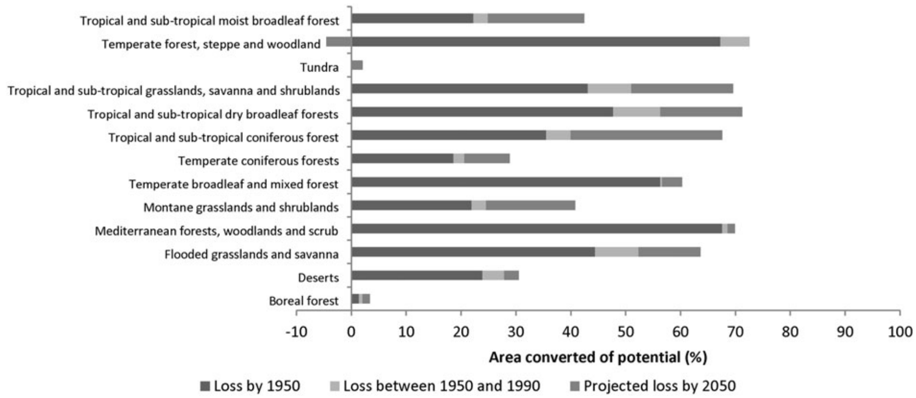

FIGURE 3 Area of key biomes predicted to be converted up until 1950, between 1950 and 1990, and the area predicted to be converted between 1990 and 2050 (adapted from the Millennium Ecosystem Assessment, 2005)

inappropriate stocking rates and grazing management practices (de Haan, Steinfeld, & Blackburn, 1997).

On a global basis, Kwon et al. (2016) categorised approximately 10% of grassland resources as degraded, that is, grasslands that will require serious intervention to recover. A greater proportion of the grassland degradation has occurred in the developing world with the most extreme degradation affecting Africa (376 Mha), Asia (244 Mha), and Latin America (157 Mha). In Asia, for example, more than 2 Mha of grasslands are being degraded every year through water and wind erosion as a result of increased pressure from livestock grazing. From the Global Land Assessment of Degradation study, Scherr and Yadav (1996) predicted that the rate of grassland degradation would accelerate by 2020, primarily through overgrazing and overexploitation of vegetation for fuel, in the trans-Himalayas and in Southern and North Africa. However, although severe degradation is a serious problem, much of the world's grasslands are in a degrading state, where shifts to less-desirable species are occurring and some productivity loss is evident. These areas can still support livestock but need better management aimed at rehabilitating them to regain their potential for delivering environmental services.

4 | ENVIRONMENTAL CHALLENGES AND OPPORTUNITIES FOR GRASS-BASED LIVESTOCK PRODUCTION SYSTEMS

Despite this degradation, grasslands still present a vast resource for domestic grazers (Blair et al., 2014), and the prosperity of smallholder pastoralists is closely tied to livestock production derived from grasslands. This means that any significant change in grassland condition will directly harm the livelihoods of millions of smallholder families. Indirect consequences to the larger population occur through biophysical (dust storms, GHG emissions, and regional climate change) and socio-economic impacts. Understanding the impact of grazing-induced degradation on the environment is crucial to developing sustainable production systems and rehabilitation programmes for degraded grassland systems. The impacts discussed here include reduced biomass, loss of biodiversity, and changes in carbon stocks and GHG emissions.

4.1 | Managing biomass production and vegetation cover

For all grassland types, maintaining both edible green and dry biomass within optimum boundaries for livestock production is the primary criterion for managing grasslands, and these boundaries are often appropriate for minimising pasture and soil degradation (Kemp & Michalk, 2007). For example, the general relationship between sheep or cattle growth and green herbage indicates that herbage mass needs to be maintained around 1.5–2 t DM/ha to achieve 90–95% of maximum liveweight gain (Kemp, Badgery, & Michalk, 2015a) although the height of vegetation and type of livestock influence this grazing interaction. These herbage mass values in temperate grasslands often equate to minimum heights of 6 and 14 cm for sheep and cattle, respectively, which are required for availability to not limit grazing intake (Graham, 2017). On the typical steppe of northern China, herbage mass levels as low as 0.5 t DM/ha have been found to be suitable to optimise sheep production and maintain pasture composition and soil carbon levels (Zhang et al., 2015). In practice, this means that grazing pressure on the grassland needs to be continually assessed and excess animals removed, moved to a new grazing area, or confined for feeding 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, Badgery, & Michalk, 2015b; Noy-Meir, 1975). Predicted increasing frequency of droughts and extreme rainfall events with climate change (Easterling et al., 2000) will pose greater challenges to managing grasslands to sustain the feed supply for livestock.

Many of the symptoms of reduced herbage mass and vegetation cover are common, irrespective of the cause of grassland degradation. If not managed well, grasslands can be overexploited with reduced productivity and loss of key species (e.g., palatable perennial grasses), a consequence due to a decreased capacity to retain water, increasing erosion risk by modifying surface soil stability and exporting nutrients and sediments to downstream water resources (McIvor, Williams, & Gardener, 1995). However, when managed using practices that retain surface cover (e.g., >70%; Sanjari, Yu, Ghadiri, Ciesiolka, & Rose, 2009) and herbage mass (e.g., >2 t DM/ha; Hughes et al., 2006), a grassland effectively controls soil erosion because it reduces raindrop impacts and aids infiltration rate by preventing surface sealing, trapping sediment, and filtering water through surface vegetation to produce good-quality runoff (Haregeweyn et al., 2013). Using appropriate management guidelines to retain grassland/rangeland cover in Australia has contributed to a sixfold reduction in the dust storm index from 11.4 to 2.0 from the 1940s to the 2000s (McTainsh, Leys, O'Loingsigh, & Strong, 2011). Well-managed grazing further reduces the negative effects of animals, from grazing and the physical action of their hooves, on soil properties (compaction, runoff, erosion, and C and N cycling; Greenwood & McKenzie, 2001). Properly managed grasslands are crucial to protecting watersheds by increasing hydrological and erosion safety, which makes the quality of water production an important product derived from grasslands.

In regions with sufficient growth potential, intensification measures such as sowing improved and deeper rooted grass and legume species can significantly increase forage productivity and quality relative to natural grassland. However, 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 & Dowling, 2000). Nevertheless, 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, Michalk, & Virgona, 2000). These practices can align with tactical management to better match livestock demand and feed supply. Simple grazing management such as tactical rest has proven beneficial when targeted at key species based on their phenology, response to grazing, and competition with associated pastures species (Kemp et al., 2015b).

4.2 | Biodiversity

Biodiversity is now threatened in approximately 300 of the 825 terrestrial ecoregions, including 23 of the 35 global diversity hotspots (FAO, 2006a). Species losses have shifted the functional composition of the vegetation, evident in widespread replacement of perennial grasses by fast growing forbs, annual grasses, and woody shrubs (Zhang et al., 2015; Moore, 1970) resulting in disruption to soil food webs (density and diversity of soil organisms). 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). In these regions, many poor farmers rely on the grasslands biodiversity to sustain the functionality of the ecosystem and their livelihoods (Jackson, Rosenstock, Thomas, Wright, & Symstad, 2009, Tscharntke et al., 2012).

Grasslands are species-rich ecosystems (Wilson, Peet, Dengler, & Pärtel, 2012), and there is a commonly held belief that retention of biodiversity is required to maintain ecosystem function. However, there are few functions that are directly linked to species richness (e.g., pollination and pest regulation; Harrison et al., 2014), rather ecosystem functions depend on species attributes that relate more to plant functional types than to species number per se. Species number does not characterise the niche individual species or functional groups fill and their role in stability, productivity, and ecosystem services (Tilman, 1999). Productivity can increase with species richness if there is complementarity rather than competition between species, particularly with regulating limiting resource such as N (Fargione et al., 2007). However, high species richness can also be associated with the loss of dominant and productive species (Kemp et al., 2003). Because a few abundant species usually account for a large proportion of grassland herbage mass within both natural and sown grassland communities, many rare species present may actually have little impact on ecosystem function. It is important to note that the relationships between diversity and function are often not linear and that a threshold in species richness exists below which ecosystem function declines and above which it may not change (Vitousek & Hooper, 1993).

Biodiversity often declines with increasing grazing pressure (Watkinson & Ormerod, 2001) because some plants have traits that are not suited to high grazing pressure (Bullock et al., 2001). Inevitably, because livestock graze selectively, some species will be defoliated more intensively, which reduces their competitiveness against less desirable species and invading weeds (Garden, Lodge, Friend, Dowling, & Orchard, 2000; Vesk & Westoby, 2001). The interactions can be complex, and the effect of grazing on plant diversity can vary with environment, soil properties, and climate (Olff & Ritchie, 1998). Furthermore, when difference in grazing pressure is moderate and around the values considered useful for sustaining the grassland, then variation in grazing pressure may not have any deleterious impacts.

In grassland landscapes, maintaining the desirable perennial species biomass through appropriate grazing management can 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). Although the optimal species number or plant functional type number is not always clear, studies such as Kemp et al. (2003) highlight that management is needed that maintains the more productive functional type (typically the desirable perennial grasses) at >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 and ground cover. A combination of several plant functional types does provide stability and maintains soil microorganism and meso-organisms (Kemp et al., 2003).

4.3 | Managing GHG emissions

Globally, livestock consume 17 Gt CO_2e/year of forage made up of 4.4 Gt CO_2e/year from crop production, 2.6 Gt CO_2e/year from crop residues and 10.0 Gt CO_2e/year from grassland and forage resources (Bajželj et al., 2014). Livestock contribute 70% of total direct emissions from agriculture (Tubiello et al., 2013) and 14.5% (Table 1) of the world's total anthropogenic GHG emissions of 49 Gt CO_2e/year (Ripple et al., 2014). Cattle produce 90% of the total GHG emissions from livestock, the majority (44%) of which is CH_4 from enteric fermentation and manure, with the balance being CO_2 (27%) emitted through land use change and fossil fuel use and N_2O (29%) from crop fertilizers and manure (Ripple et al., 2014). Between 1960 and 2010, global CO_2e emissions from the livestock sector increased by 51% (Caro, Davis, Bastianoni, & Caldeira, 2014), due mainly to increases

TABLE 1 Livestock sector GHG emissions in Gt CO_2e/year (adapted form Ripple et al., 2014 using FAOSTAT data for 2011)

Livestock number/source of GHG emissions	Ruminants				
	Bovine[a]	Ovine[b]	Total	Monogastric[c]	Total
Total number (billion)	1.6	2.0	3.6	20.0	23.6
CH_4 emission (Gt CO_2e/year)	2.29	0.22	2.51	0.62	3.12
CO_2 emission (Gt CO_2e/year_	1.40	0,14	1.54	0.38	1.92
N_2O emission (Gt CO_2e/year)	1.50	0.14	1.64	0.41	2.06
Total emission (Gt CO_2e/year)	5.2	0.5	5.7	1.4	7.1

[a]1.4 billion cattle and 0.2 billion buffalo;

[b]1.1 billion sheep and 0.9 billion goats;

[c]19 billion poultry and 1 billion pigs.

in beef and dairy cattle numbers, which rose by 117% in developing countries but fell by 23% in developed economies.

Deforestation, now occurring largely in tropical areas for the expansion of pasture and cropland, has become a major source of GHG emissions; part of which is then attributed to livestock. The conversion of forests to poorly managed grazing lands (Soussana, Klumpp, & Ehrhardt, 2014) and to cropland (palm oil in south-east Asia) contributes to a significant quantity of global GHG emissions, estimated at 450–800 Gt CO_2 from biomass and soil carbon pools (Olofsson & Hickler, 2008; Shevliakova et al., 2009). Lowering demands for beef or improving production efficiency of the current cattle herd would reduce the need for further 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 deliver a mitigation potential of approximately 2.3–5.8 Gt CO_2e/year. However, it is unlikely that these changes would occur at anything like the rate required, unless better targeted management programmes were in place.

Net carbon sequestration in soil and vegetation, in grassland through better land management, is a proactive mitigation pathway with a potential of approximately 1.5 Gt CO_2e/year to 2030. Additional mitigation is possible from restoration of degraded lands with a C sequestrate rate of 0.04 to 1.1 Gt CO_2e/year (Smith et al., 2007) and expected rates of change to average 0.28 t $CO_2e{\cdot}ha^{-1}$ yr^{-1} (Conant, Cerri, Osborne, & Paustian, 2017). These gains could be achieved by better management of grazing of plants to encourage extensive root systems for storing C. Plant species used in the grassland need to be adapted to the local climate, tolerate grazing and drought, and capable of building soil fertility (e.g., N-fixing species) as well as being of higher forage quality for livestock. Better management of soil water and nutrients, especially N, is critical to encourage plant growth (Bajželj et al., 2014; St Clair et al., 2009), so that over time, the grasslands become a C sink (Chen et al., 2015; Lee, Manning, Rist, Power, & Marsh, 2010). C sequestered by the grassland can then be offset the GHG production by livestock. Grazing management is the main tool available for farmers to aid plant management and then optimise C management within a grassland, but the results would be variable, depending upon climate, soil nutrients (Pineiro et al., 2010), and grassland composition (McSherry & Ritchie, 2013).

Sowing pasture species that are adapted to the local climate, tolerate grazing, are more resistant to drought, and are capable of building soil fertility (e.g. N-fixing species) can significantly increase production and forage quality. Soil C sequestration though can be degraded through several processes associated with climate variability and poor management such as soil disturbance, degradation of vegetation through overgrazing, fire, erosion, nutrient shortage, and water deficit (Soussana et al., 2014). Nevertheless, it is a realistic expectation that approximately 10% of grazing lands globally could be placed under C sequestration management by 2020 (Conant, 2010).

Although grazing livestock contribute significantly to GHG emissions, 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 the effectiveness of improved management will depend on locating areas where these practices will work (Henderson et al., 2017). For example, Thornton and Herrero (2010) showed that a 10% improvement in digestibility of stover and increasing grain supplement from 0.5 to 2 kg per head per day both effectively reduced CH_4 emission in cattle. However, in practice, treating crop residue is likely to be more effective because it has wider application across most rain-fed mixed systems in developing countries where approximately 63% of cattle are raised (Gerber, Henderson, Opio, Mottet, & Steinfeld, 2013) and stover comprises 50% of the diet of ruminants (Herrero et al., 2013). Feeding grain concentrates may be more appropriate in humid and temperate mixed systems.

Although 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 also increasing productivity by improving animal husbandry (e.g., less grazing and better quality feed; improved breeding; and better disease control), refining grassland management practices, and/or rehabilitating degraded grasslands (Havlík et al., 2014). This is good news for the developing world where 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 (Godfray & Garnett, 2015). Rather more work is needed to develop and test appropriate management practices unique to grassland types before promoting large-scale implementation by small holders in developing countries (Henderson et al., 2015). 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 red meat consumption should be significantly reduced or eliminated and replaced by a vegetarian diet. That clearly ignores the reality of many countries, particularly those in the developing world where red meat offers valuable nutrition especially when other protein sources are limited and where there is a real increasing demand for red meat as incomes rise. It is also a simplistic argument that does not account for the full impacts of these changes (e.g., how much extra crop and N fertiliser is required to substitute protein in the world's diet). The way forward is to evaluate management options using 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.

5 | WHAT ROLE FOR SMALLHOLDERS IN THE SUSTAINABILITY OF THE 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 (Havlík et al., 2014). 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 (Havlík 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 yields per animal) through improved efficiency (Herrero, Grace, et al., 2013). Projections show that livestock numbers will still increase, 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 & Herrero, 2010) will play a more important role in red meat production to reach 2050 targets, whereas higher off-take rates (shorter production cycles) will be more important for grazing livestock in developing countries where the potential gains are much greater. Stocking rates on grassland are effectively reduced by improving efficiencies that result in early weaning and in livestock reaching a marketable size earlier and being sold at a younger age.

Even with improved technology and better market access, some question the sustainability of livestock farming, which is considered to use 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 & O'Riordan, 2015). However, despite the catalogue of negative impacts evident in the loss of biodiversity, high consumption of fresh water, and GHG emissions, these impacts may not be as great as claimed. For example, the large footprint on water resources is a clear example of where these assessments are misleading (Ridoutt et al., 2012; Ridoutt, Sanguansri, Nolan, & Marks, 2012). Furthermore, in the developing world, livestock generally use land that is either unsuitable for crop production or integrated with cropping systems to utilise residues (Thornton & Herrero, 2010). 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 meeting the challenge of feeding the world sustainably (Herrero et al., 2013).

Inevitably, although problems are global, the solutions are generally local and situation specific (Herrero, Grace, et al., 2013). For this reason, more than 1 billion smallholder livestock keepers who produce approximately 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 (Herrero & Thornton, 2013; Kemp & Michalk, 2011a). 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? We believe the answer to both of these questions is yes. 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)? There is a case for both, but where there are no established markets for extra product or capacity to pay for it, then increased efficiency may not reward the small holder.

TABLE 2 Meat production: Number of animals and carcass weight (FAOSTAT; Alexandratos & Bruinsma, 2012)

	Number of animals (millions)			Average carcase weight (kg)		
Livestock type	1963	2007	2050	1963	2007	2050
	Developing 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	2,568	5,239	7,212	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	1,867	13,921	29,817	1.1	1.4	1.6

5.1 | Difference in production efficiency between developed and developing countries

Livestock production systems are shaped by the linkage between demand and resource supply (Noy-Meir, 1975). 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, and 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.

Developing countries, with extensive grassland areas, often have a long history of small holder farming and livestock keeping, but increasing and more settled human populations have meant that traditional practices, such as transhumance grazing, are no longer viable. Traditional management of the animals was primarily about survival, rather than production; they were 'users' and, or 'keepers,' but not 'producers' (Kemp & Michalk, 2011b; Neidhardt, Grell, Schrecke, & Jakob, 1996). This in in contrast to developed countries, where supply chains are better established and systems are more product focused.

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 are driven mostly by increasing livestock number, whereas in developed countries, the livestock population has remained constant, but the output per animal evident in carcase weight and shorter production cycles has increased significantly, reflecting improved production efficiency (Table 2). More importantly, Table 2 highlights an enormous 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?

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

Industry-wide statistics for the Australian sheep industry clearly demonstrate that the efficiency gains made possible through the application of sustainable intensification. In 1980, Australia had approximately 150 M sheep raised on 56,000 farms, which produced a total sheep carcase weight (cw) of 530,000 cw t compared with 2016 when Australia had approximately 68 M sheep raised on 31,000 farms that produced 670,000 cw t (ABS, 1982; MLA, 2017). This represents a 55% reduction in sheep numbers and 24% 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 select more desirable species within those pastures. Strategies to improve the quality and length of growing season, such as increasing the use of forages like *Medicago sativa*, will improve the efficiency of finishing lambs to market specifications. This will also result in improved ewe condition, leading to a higher conception and weaning rates (Behrendt et al., 2011), which also means less ewes need to be carried throughout the year.

Selecting the best genetics, breeding systems, and grass-fed management strategies has helped increase lamb carcase weight to 22 kg per head in 2012, 30% higher than the predicted carcase weight for 2050 (Table 2), although increased carcase weights have been partly due to larger animals, which require greater pasture intake (Graham & White, 2015). 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 the 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, Wu, Badgery, & Kemp, 2015). Just as important is the sequence of National programmes such as Prograze (Bell & Allan, 2000), Sustainable Grazing Systems (Mason et al., 2003), Grain and Graze (Bridle & Price, 2011), and EverGraze (Badgery, Michalk, & Kemp, 2015; Michalk, Badgery, & Kemp, 2017) that have clearly built the knowledge required and 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 programmes 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 breeding flock totalled 140 M with a total meat production of 2 Mt at an average carcase weight of approximately 16.7 cw kg per head for the 120 M sheep slaughtered (Chinese Statistical Yearbook, 2012). In contrast, Australia's sheep flock totalled approximately 72 M and produced 640,000 t of meat with an average weight of 22 cw kg per 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 Chinese sheep flock could be significantly reduced and still produce 2 Mt of sheep meat. 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.

5.3 | Transition from subsistence to market-oriented livestock production

Developing strategies and tactics that better align the balance between forage supply and animal demands underpin 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. Because 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 'user/keeper' of livestock to a 'producer'/market-oriented system (Kemp & Michalk, 2011b; 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, Michalk, Kemp, Yang, & Gong, 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 et al., 2013; Kemp et al., 2015a, 2015b; Kemp & Michalk, 2011a). 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 initially rising, then falling once animal production per head is half of their potential (Jones & 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, the optimal financial position, where grassland management is also optimal, being where animal production per head is approximately 75% of potential. Focusing on productivity per head provides better guidance to farmers than a fixed stocking rate.

Because many farmers (and especially smallholders) are grazing forage resources well beyond the economic optimum and because 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., 2013; Kemp & Michalk, 2011a; Thornto, Herrero, & Ericksen, 2011). Balancing livestock needs with current forage supplies will provide smallholders with the greatest opportunity to increase profit by producing more valuable products (Kemp & Michalk, 2011a). 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 overgrazing that are typical of traditional livestock systems (Briske et al., 2015) causing a successional shift in composition back to a more desirable state. However, this is not always the case due to the loss of soil seed reserves of desirable species and/or completion of invasive unpalatable weeds preventing their re-establishment (Westoby, Walker, & Noy-Meir, 1989). Local research is needed to resolve, which are the better grazing tactics and strategies to facilitate grassland regeneration.

This transition of smallholders to commercial production requires different skills to deal with the technology and decision-making that underpins the management of modern livestock production systems that are market focused. Disadvantaged herders often have limited skills and knowledge to make decisions in a market economy as their skills have been focused on survival, and they are limited 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 are unaware or uncertain (Wu et al., 2011).

6 | CONCLUSION

Is there a sustainable future for the demand-driven world's livestock sector? This review agrees with other assessments (Herrero & Thornton, 2013; Thornton, 2010) that demand for red meat products, driven by human population growth, increasing incomes, and urbanisation, 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 overexploitation 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 (Godfray & Garnett, 2015; Kemp & Michalk, 2011a). 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. This has been demonstrated for herders in semiarid grasslands in China (Kemp et al., 2013; Kemp & Michalk, 2011a). The constraints to achieving sustainability across the livestock sector are not technical but are sociological, economic, and political.

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