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Environmental impacts of beef production: review of challenges and perspectives for durability.

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Abstract:

Beef makes a substantial contribution to food security, providing protein, energy but also essential micro-nutrients to human populations. Rumination allows cattle – and other ruminant species – to digest fibrous feeds that cannot be directly consumed by humans and thus to make a net positive contribution to food balances. This contribution is of particular importance in marginal areas, where agro-ecological conditions and weak infrastructures do not offer much alternative. It is also valuable where cattle convert crop residues and by-products into edible products and where they contribute to soil fertility through their impact on nutrients and organic matter cycles.

At the same time, environmental sustainability issues are acute. They chiefly relate to the low efficiency of beef cattle in converting natural resources into edible products. Water use, land use, biomass appropriation and greenhouse gas emissions are for example typically higher per unit of edible product in beef systems than in any other livestock systems, even when corrected for nutritional quality. This particularly causes environmental pressure when production systems are specialised towards the delivery of edible products, in large volumes.

The paper discusses environmental challenges at global level, recognizing the large diversity of systems. Beef production is faced with a range of additional sustainability challenges, such as changing consumer perceptions, resilience to climate change, animal health and inequities in access to land and water resources. Entry-points for environmental sustainability improvement are discussed within this broader development context.

Key words:

Cattle; production systems; feedlots; natural resource use; sustainability; mitigation.

1. Introduction

Within the livestock sector, beef emerges as the commodity receiving most attention for its environmental impacts. This is due to the evident aggregated contribution that beef production makes to global environmental issues such as climate change and land use. Globally, beef supply chains are estimated to emit about 2.9 Gigatonnes of CO2-eq, about 40% of all livestock emissions using a life-cycle approach (Gerber et al., 2013). The greenhouse gas emissions per unit of product (emission intensity) peak where beef is produced on newly deforested land (Cederberg et al., 2011). Cattle are also the dominant ruminant specie making use of about one quarter of all emerged lands (Steinfeld et al. 2006; Bouwman et al. 2005). These issues are amplified by public health concerns related to high consumption levels and pollution from intensive production (Walker 2005) as well as a growing attention to animal welfare (Petherick, 2003; O'Donovan and McCarthy, 2002).

The world has over 1.3 billion cattle – about one for every five people on the planet (FAOSTAT, 2015). While cattle are kept and raised for the wide range of products and functions they deliver, the vast majority is eventually culled and served as meat. Beef production thus takes multiple forms and involves a wide range of supply chains. The debate on beef production, and on livestock more generally, is however too often characterized by a lack of recognition of this tremendous diversity in production systems, in the goods and services they deliver as well as in the environmental interactions and options for improvement that exist (Smith, 2015). The general perception of beef production is biased towards specialized factory farming, while these represent a limited part of a sector that is still dominated by family farms operating on mixed-systems (Herrero et al., 2013).

This paper aims at providing a global overview of beef production systems, their diversity and their contributions to society. It also reviews how beef supply chains contribute to major global environmental issues and identifies specific entry points for intervention.

2. Cattle: their biology, diversity and related comparative advantages with other livestock species

The specificity of ruminant production, its contribution to human societies and its interactions with their environment is deeply rooted in the biology of ruminants. Three features stand out: digestion, reproduction and diversity.

1.1. Digestion

The digestive track physiology determines the feed materials that animals can effectively utilize but also the efficiency with which nutrients in feed materials are used. Ruminants are well known for their ability to digest feed materials rich in cellulose and fiber (low in energy and typically only 50-65% digestible), in contrast to non-ruminants (Figure 1). This is made possible by the microbial fermentation that occurs in the rumen. The products of this fermentation are absorbed by the animal in the following small intestines. This makes them able to develop in conditions where monogastric species are excluded, and places them in a unique position to turn resources inedible by humans into high value food products but also into other outputs such as fiber, fertilizer and draft power.

The energy-efficiency of microbial fermentation is however limited by the emission of enteric methane (CH_4). It is estimated that about 8-12% of the energy in a feed is lost through methane and cannot be utilized by animal. This is an issue for the producer, but also for the environment given methane's global warming potential. In a similar way, ruminants are not particularly efficient in using high quality dietary proteins: a high share is broken down in the rumen and partially used for microbial growth, resulting in ammonia exhalation and losses of N in faeces (Opio et al., 2013).

1.2. Reproduction

Reproduction performance (driven by fertility, prolificacy and mortality among offspring) is a key driver of population dynamics and thus of productivity, essential to the replacement of milked cows and to the production of fattening animals. However, a cow is likely to produce at best a single calf per year, and commonly produces a viable calf every 1.5 to 2 years (Ball and Peters, 2004). This is much lower than for other ruminant and non-ruminant species that are generally more fertile and prolific (Table 1). In addition, cows typically become fertile at later age than females of other species. This results in a greater share of the animal herd that is dedicated to reproduction (the "reproduction overhead"), compared to other species, and therefore an increased part of the metabolizable energy that is dedicated to maintenance at herd level. It is thus estimated that between 50 and 80% of total metabolised energy is used for maintenance (Opio et al., 2013). Further effects of late age at first calving, and relatively limited fertility and prolificacy are the slow nominal growth of herds, particularly problematic after crisis that may have caused drastic falls in animal numbers, and the reduced pace at which new genes can be introduced into the herd. Cows that fail to reproduce are culled, limiting the choice of animals available to produce replacements and thus limiting genetic progress (Ball and Peters, 2004).

Table 1. Main reproduction features among dominant livestock species.

	Gestation (days)	Offspring/female/year (mortality not included)
Sheep	147	1-3
Beef	270	1
Dairy	270	1
Pig	114	7-14
Poultry	22-22	100-300

Source: Gordon (2004)

1.3. Diversity and hardiness

Cattle and buffalo breeds represent 25 percent of the world's 10,512 recorded mammalian livestock breeds, a similar share than sheep, followed by horses, goats and pigs, all around 12 to 14%. For comparison, only 3,505 avian breeds are reported, of which chicken represent 60% (FAO, 2007). Thousands of years of migrations and trade spread domesticated animals from their original habitats, exposing them to new agro-ecological conditions. South Asian Zebu cattle were for example introduced in Latin America during the early twentieth century, and now support most of the production in this major producing and exporting region (FAOSTAT, 2015). Natural selection, human-controlled breeding gave rise to the great genetic diversity observed today (FAO, 2007).

In all regions of the world, reported mammalian breeds outnumber avian breeds (FAO, 2007). This large diversity reflects a tight adaptation of mammals, and cattle in particular, to their environment and to the needs of the human populations looking after them. Resistance to diseases (e.g. to trypanosomiasis), and tolerance to particularly harsh climatic conditions, and poor feed quality are among the traits that have placed cattle, together with small ruminants, in a position to sustain livelihoods and human settlements where crop agriculture and other mammalian and avian species could not.

In more favorable agro-ecological conditions, selection among and within breeds as well as the use of crossbreeding to exploit heterosis have allowed to reach high levels of productivity and quality, expressed in daily weight gains, conformation and fat to muscle ratio (Cundiff et al., 1986). For example, McKay et al (1989) have reported that live weights of cows can vary from 488 kg for a cross bred Hereford x Angus, to 594 kg for a cross bred Charolais x Angus. This compares for example to live weight of female zebu cattle varying from 162 to 207 kg in Nigeria, under different diets (Mukasa-Mugerva, 1989).

In parallel to these breeding programs, the conservation of traditional cattle breeds diversity is also receiving increased attention to halt the erosion of livestock genetic resources, which is recognized as crucial for food security, rural development and agriculture sustainability (FAO, 2007). Breed conservation is often conducted in association to the conservation of cultural and historic aspects of rural life and landscapes. The Global Plan of Action for Animal Genetic Resources (Hoffmann & Scherf, 2010; Hoffmann, 2011) has been adopted by 109 countries and includes 23 strategic priorities for action to promote the wise management of these vital resources. Countries have so far implemented more than half of the identified actions.

The genetic potential of breeds is a strong driver of their performance, especially with regard to digestive and reproduction capacities, which are important determinants of production systems and of their efficiency in using natural resources. This could be looked at as a "biological potential" regarding productivity and environmental interactions. Animal management does however define the actual productivity and impact levels.

3. Cattle production systems and contribution to food security

Cattle production occurs within a myriad of different agro-ecological conditions and production systems, relying on diverse breeds, and producing a range of goods and services. Understanding these differences in production practices is necessary to assessing the contribution of different systems and unraveling key drivers of environmental interactions, as well as proposing development pathways (Bouwman et al., 2005).

The type and source of feed given to the animals and particularly the share of grazing in the feeding system are key driver of this diversity. Herd management and the level of market integration further contributes to the defining production systems.

1.1. Grazing systems

Sere and Steinfeld (1996) defined as grazing the systems where more than 90% of dry matter (DM) fed to animals comes from rangelands, pastures and annual forages, and less than 10% of the total value of production comes from non-livestock farming activities. Grazing systems supply about 34% of global beef production (Table 2). They cover the largest land area, across all climatic zones, as shown in Figure 2.

The most extensive forms of grazing systems have developed in harsh environment, such as dry lands and cold areas. In these conditions that are predominantly unsuitable for crop production, feed and water shortages can affect animals during part of the year. Production is thus often mobile and relies on communal land (pastoral and nomadic systems). Cattle herds in these conditions serve a large number of functions, supplying food, but also transportation, fibber, banking and insurance. Animals are kept longer than in other systems, spend more energy on movements, and the herd structure is adapted to multi-functionality and to buffering against shocks and crisis. As a consequence, these systems are generally characterised by relatively low productivity in terms of edible products; at animal level (even correcting for the relative light weight of animals), and especially at herd level (Opio et al., 2013). Average daily weight gains, milk yields and age at first calving, are typically low while mortality is high. Their market integration is further limited by deficient transport and communication infrastructure.

The total supply of these systems is estimated to account for less than 15% of total beef production (own calculation, based on FAO 2009). While they are well adapted to a scare and erratic resources and have traditionally been resilient to harsh climate these systems face issues in adapting to new challenges, related to competition for resources with sedentary agriculture, political instability, lack of representation in modern institution and climate change (Touré et al., 2012).

More intensive grazing systems are found in tropical and temperate zones where high-quality grasslands and fodder production can support larger numbers of highly productive animals. These systems are mostly focused on food production and based on individual landownership and are well connected to markets. They supply about 20% of global beef production.

1.2. Mixed systems

Mixed farming systems are defined as those systems in which more than 10 percent of the dry matter fed to animals comes from crop by-products or stubble or where more than 10 percent of the total value of production comes from non-livestock farming activities (Sere and Seinfeld, 1996). Gerber et al. (2013) further divide mixed systems in those that produce both milk and meat ("dairy herd") and those that only produce meat ("beef herd").

Mixed systems account for the bulk of cattle population (over 60%) and a similar share of beef output (Table 2). These figure are in line with those estimated by Herrero et al. (2013). On a global scale, the dairy and beef herd contribute equally to the beef output (Table 2), however large regional variation exists and the milk herd dominates beef outputs in regions such as Western Europe or South Asia. It should be noted that dairy farms operating at relatively high levels of intensification are classified here as mixed systems.

1.3. Feedlots

In contrast to mixed and pastoral production systems, feedlot, are almost exclusively dedicated to food production, as a response to growing demand for beef in urban areas.

The vast majority of feedlot feed is purchased off-farm: beef cattle in feedlots are mostly fed on purchased grain, sometimes up to 95% in DM (70 to 90% in the US). Feedlots are also characterized by high energy rations and high daily weight gains. The operations are usually large in size but simple in terms of equipment, fully mechanized and vertically integrated. There is thus a greater uniformity of technology and practices than in mixed and grazing systems. Feedlots are often coupled with mixed or grazing systems, from which they acquire young animals (weanlings or yearlings), for fattening until they reach a standard weight for slaughter. Today about 2% of global cattle population is estimated to be held in feedlots and produce about 7% of the global beef production (the latter includes animals previously on other production systems) (Table 2).

Beef production from feedlots is expanding throughout the world (Figure 2). Feedlots are well established in countries like the US or Canada, and rapidly growing in other regions, such as South America, Asia and Africa, driven by raising demand for meat in urban areas. Feedlots also provide the kind of standardized carcasses requested by the retail sector, and make use of relatively cheap crop products and co-products as well as by-products such as soybean cakes and Dried Distillers Grains with Solubles (DDGS). Feedlots usually have high animal performance levels in terms of average daily weight gain and feed conversion ratio. This often results in relatively high levels of natural resource use efficiency (Pelletier et al., 2010, Capper 2012), although typically lower than industrial poultry and pig operations. Feedlot operations are nevertheless associated with relatively high impacts on water resources and air quality, mostly due to the geographical concentration of production units (Vasconcelos et al., 2007).

Table 2: Global cattle population and beef production by production system in 2010

	Grazing	Mixed	Landless (feedlots)	Total
Cattle population	35%	63%	2%	1446 million heads
Beef production	34%	Dairy herd: 28%	7%	66 million tonnes
		Beef herd: 31%		

Note : « dairy herd » refers to milked cows and all related animals (including meat animals), and « beef herd » refers to all other cattle.
Source: GLEAM (Gerber et al., 2013)

Farming system classification is a convenient and effective way to structure our analysis and recommendations. It is however important to keep sight of the tremendous diversity that exist within our broad system classification, and also of the dynamics that do exist between classes. First, transition is taking place from grazing to mixed systems, often driven by population density, but generally at limited pace, constrained by agro-ecological conditions and access to finance, markets and technology. Intensification within mixed systems and from mixed systems to feedlots is quite faster (Bouwman, 2005), especially where market demand is strong, feed available and environmental regulations favorable.

1.4. Contribution to food security

The authors propose the following five essential determinants to explain the level of contribution that cattle make to food security:

First, the feed ration of the animals, and whether the materials included in the ration are used or produced in concurrence with human edible food. This is for example the case of grains and fodder crop cultivated on arable land. On the contrary, crop residues, food by-products and fodder produced on non-arable lands are not directly comestible by humans, although they could contribute to food production through fertilization and energy production. Figure 3 shows the estimated composition of the global feed ration of cattle. Although it can be argued that a part of the "fresh grass and hay" is actually produced on crop land, the vast majority of the ration is made of materials not edible by humans.

Second, the efficiency with which the herd converts feed into edible products (kg of feed per kg of beef). This efficiency is driven by (i) the quality of the feed, (ii) the animal performances (e.g. growth rates, influenced by genetics and health conditions), (iii) the proportion of breeding stock in the herd (these animals need to be fed but do not contribute directly to the edible product output); and (iv) the proportion of meat supply from dairy herds, since in the dairy herd, maintenance energy is diluted over the two products. Looking at Figure 4, feed conversion can be expected to be poor where maintenance drains a large part of the metabolized energy.

Third, the contribution cattle makes to agricultural productivity, e.g. through manure and draught power used in crop production. For example, Gebresenbet & Kaumbutho (1997) estimate that cattle, together with camels, horses and donkeys, provides transport and draught power for ploughing fields for about 15% of farms in Southern Africa and 81% of farms in Northern Africa. In Europe, the share of manure input in total Nitrogen inputs was estimated at 38% and reaches 61% in the Netherlands (European Commission, 2012).

Fourth, the availability and affordability of other sources of foods and in particular protein and micro nutrients, and thus the exclusive or optional nature of beef contribution to nutrition.

And fifth, the income generated by cattle production at household and national level. Today, an estimated 15% of total beef and 17% of total milk production is exported, with a few countries only (Australia, Brazil, India and USA) generating substantial revenues, accounting for 10 to 12% of world export each. In parallel, least developed countries find themselves increasingly dependent on imports of cattle products: the share of imports in consumption increased from 1% in 1960 to over 8% in 2010, and in 2011, least developed countries were net importers of 90 thousand tons of beef (FAO, 2015).

These factors will vary locally in a multitude of combinations. On a general level, it can nevertheless be summarized that cattle play a dominant role in food security in pastoral systems, cattle are a major source of food and income. Furthermore, livestock products are accessible and marketable at any time, allowing to buffer against crisis. In mixed systems, cattle contribute directly to food security by converting forages and agro-industrial by-products such as cereal brans and cakes into nutritious food. They also contribute to agriculture productivity by supplying draught power and manure. In contrast, cattle in feedlots make a limited contribution to food security and rural livelihoods (Wilkinson, 2011). Part of the feed they ingest could directly serve as food or has been cropped on areas where food could have been produced. Furthermore the efficiency with which feed is converted into animal products is lower than for monogastrics.

5. Interactions with the environment

A large part of our ecosystem is managed for cattle production, through a variety of practices and at a range of intensification levels. It is thus not surprising that the sector has strong and diversified interactions with the environment.

1.1. Land and water

Feed production, whether pasture or crops, is the main activity through which cattle use land and water resources (Steinfeld et al., 2006). Over 60% of the global cattle feed ration (in DM terms) is made of grass and tree leaves (Figure 3). Land occupancy related to the production of these material (for all ruminants) is estimated at about a quarter of emerged land (Steinfeld, 2006), and management practices range from intensively managed pastures (planted and fertilized) to rangeland that are used occasionally depending on rainfall.

The other 40% are mostly crop residues (about 30%), but also crop products and by-products. The global production of feed crops (for all livestock species) is estimated to mobilize about one third of global cropped area (Gerber, 2013). While co-products are frequently used among mixed-systems, grains and by-products are mostly used in intensive dairy operations and feedlots. They are generally sourced from industrial crop production, and thus contribute to environmental issues such as eutrophication, water depletion and emission of pesticide into the environment (Tilman et al. 2002).

The DM intake per unit of edible product is usually much higher for ruminants than monogastrics (Bouwman, 2005). Furthermore, monogastric feed (mostly cropped) is less land intensive than ruminant feed (mostly grass and tree leaves). This converges into relatively high land occupancy per unit of beef production compared to other livestock commodities. Based on a literature review, de Vries and de Boer (2010) report that in OECD countries, the production of 1 kg of beef uses 30 to 50 m^2, compared to areas inferior to 15 m^2 for the production a kg of chicken, pork, egg or milk - although it must be highlighted that the way the land is used is not the same.

Land requirements per unit of beef varies significantly between regions (Figure 5). There is no apparent relation between the reliance on grassland/cropland and the land occupancy per kg of product. Grasslands dominate in all regions but South Asia, where mixed systems relying on crop residues are particularly common. Figure 5 further shows regional trends in the place of imported feed. Off-farm land use is relatively important in industrialized regions, but also in North Africa and the Middle East.

Mekonnen & Hoekstra (2012) estimated that beef cattle was responsible for 33% of the global water footprint of animal production and to almost 10% of the global water footprint of total agricultural production. Importantly though, these figure amalgamate different categories of water: blue water (diverted from surface and groundwater, usually for irrigation and servicing), green water (rainwater evaporated from soil and plants in rained crops and pasture) and grey water (needed to assimilate the load of pollutants, such as discharged manure and waste water). Among these, it can be argued that green water consumption has virtually no environmental impact given the fact that natural ecosystem would have similar levels of evapo-transpiration (de Boer et al., 2012). If the beef green water footprint largely surpassed those of pig and chicken meat (by a factor 3 to 4), its blue and grey water footprints are actually of a similar magnitude: 550 and 451 for beef respectively, as compare to 313 and 467 for chicken meat and 459 and 622 for pig meat (Mekonnen & Hoekstra, 2012). Beyond these global averages, it is however the wide range of local situation that deserves attention: the same authors find grey water footprints ranging from 0 m^3 per ton (Grazing systems in India) to 1,234 m^3 per ton (Industrial systems in China), and green water footprints ranging from 2,949 m^3 per ton (Industrial systems in the USA) to 25,913 m^3 per ton (Grazing systems in India). Farm level variability will be even greater than these averages at country/system level.

1.2. Nutrient cycles

Cattle are estimated to excrete 56 to 60% of the yearly 75 to 138 Tg N excreted by all livestock (Oenema, 2005). The relatively low efficiency of nutrient retention not only represents a major economic loss but also places a burden on the environment (Sutton et al., 2013). In general terms, between 55 and 95 % of the nitrogen (N), and about 70 % of the Phosphorus (P) ingested by livestock is excreted as urine or faeces (Menzi et al., 2010). Part of this manure is recycled and fertilizes pastures and crops but a large share is lost to the environment, through gaseous emissions, leaching and runoff (Eckard, 2007; Castillo et al. 2000). Figure 6 illustrates the proportion of feed nitrogen retained by dairy and beef herds. Efficiencies are generally greater in regions where feed is balanced and tuned to the needs of animals. They however hardly exceed 30% in the dairy herd and 15% in the beef herd. Animal level efficiency, measured on productive animal is usually greater than herd level efficiency. This is confirmed by Figure 7 for milked cows (which N efficiencies ranges between 15 and 35 %, but not for beef animals, probably due to the limited representativeness of reviewed studies. P use efficiency is generally greater, ranging between 19 and 60% for milked cows and between 14 and 28% for fattening animals. Figure 7 further shows that efficiency levels, although spreading over large ranges, are typically lower for cattle than for other species. This causes severe environmental impacts where feeding or dairy operations concentrate in confined geographical areas and nutrient excretions substantially exceeds the absorption capacity of the land (Menzi and Gerber, 2006). Oenema (2005) reports N input–output budgets of 10, 115 and 126 kg/ha/year for extensive, grass-clover and fertilized grass-based systems. Generally, the author reports that N losses per ha increase as we move from grazing systems to mixed systems and feedlots.

1.3. GHG emissions

Livestock contribute to climate change by emitting GHGs either directly (e.g. from enteric fermentation and manure management) or indirectly (e.g. from feed-production activities, conversion of forest into pasture). Based on a Life-Cycle Assessment approach, it is estimated that the sector emits about 7.1 gigatonnes of CO_2 equivalent, about 14.5% of the total anthropogenic GHG emissions (Gerber *et al*., 2013).

Cattle are the main contributor to the sector's emissions with about 4.6 gigatonnes CO_2-eq, representing 65 percent of sector emissions. Beef cattle (producing meat and non-edible outputs) and dairy cattle (producing both meat and milk, in addition to non-edible outputs) generate similar amounts of GHG emissions. Beef contribute 2.9 gigatonnes CO_2-eq, or 41 percent, and cattle milk 1.4 gigatonnes CO_2-eq, or 20 percent, of total sector emissions.

When emissions are expressed on a per protein basis, beef is the commodity with the highest emission intensity (amount of GHGs emitted per unit of output produced), with an average of over 300 kg CO_2-eq per kg of protein; followed by meat and milk from small ruminants, with averages of 165 and 112 kg CO_2-eq per kg of protein, respectively (Figure 8). Different agro-ecological conditions, farming practices and supply chain management explain the great heterogeneity, observed both within and across production systems.

There is a distinct difference in emission intensity between beef produced from dairy herds and from specialized beef herds: the emission intensity of beef from specialized beef herds is almost fourfold that produced from dairy herds (68 vs. 18 kg CO2-eq per kg of carcass weight) (Gerber et al., 2013). This difference is primarily due to the fact that dairy herds produce both milk and meat while on the other hand, specialized beef herds mostly produce beef. As a consequence, emissions from dairy herds are attributed to milk and meat while emissions from beef herds are allocated to meat (in both cases, a limited fraction is allocated to other goods and services, such as draught power, and manure used as fuel). A closer look at emission structure shows that emissions from reproductive animals (the “breeding overhead”) exclusively explain the difference: when only fattening animals are considered, specialized beef and surplus dairy calves have similar emission intensity per kg of carcass weight. In addition, the breeding cohorts represent 69 percent of the herd in specialized beef herds, compared with 52 percent in dairy systems.\

1.4. Biodiversity

Biodiversity is considered as an impact located at the *endpoint* of environmental mechanisms. It means that the interactions between beef production and the environmental categories described above – GHG emissions, nutrient cycles, land and water use – have, in turn, an impact on biodiversity. Several pathways of impact on biodiversity exist and importantly, they range from negative to positive effects.

Because of its important land use, beef production modifies many habitats. One type of habitat modification is the destruction of undisturbed habitats, as the conversion of the Amazonian rainforest to pastures and feed crops (soybean in particular). Amazonian rainforests are biodiversity hotspots, they may host up to a quarter of the world’s terrestrial species (Dirzo & Raven, 2003). The destruction of this habitat led to important biodiversity losses, although it is recognized that beef production is not the only driver of deforestation, which has been significantly reduced since 2004.

A second type of habitat modification is land degradation. It results from the combination of inappropriate grazing management (overgrazing in particular) and climatic factors. Depending on regions, land degradation lead to desertification or woody encroachment, both accompanied by biodiversity losses (Asner et al., 2004).

A third type of habitat modification yields positive biodiversity effect; is the maintenance of semi-natural grassland habitats. In Europe, grassland habitats are among those with highest biodiversity levels because the long history of livestock farming provided time for a large pool of species to adapt and specialize (Bignal & McCracken, 2000). Extensive and appropriate grazing management is key to maintaining these habitats and their rich biodiversity. When abandoned, they “close” into shrubland and ultimately forests which often have a lower conservation value. Beef production has a significant contribution to this type of extensive management and its positive effect on biodiversity has also been evidenced in other regions (e.g., China, US).

Mixed and industrial beef production systems could also have a positive effect on biodiversity if intensifying the production was a way to spare undisturbed habitats for biodiversity conservation. However, specific intensification practices would have to be adopted in order to mitigate the other types of negative effect that these systems can have on biodiversity, through pollution in particular. Moreover, intensification does not automatically lead to spare land for biodiversity conservation, strong policy frameworks are thus necessary (Ewers et al. 2009).

Climate change is an increasingly important driver of biodiversity loss; Thomas et al. (2004) estimated that 15 to 37% of the species in their global studied sample would be “committed to extinction” by 2050, due to climate change. Although beef production has a significant contribution to anthropogenic GHG emissions, isolating its responsibility in the biodiversity loss due to climate change would be complex.

The link between nutrient pollution caused by beef production is more direct. In industrial to mixed system, such pollution occurs at several stages of livestock production. Upstream, it is related to the fertilization of feed crops. A striking example is the nutrient loading in the Mississippi River due to broad fertilizer use in the central US croplands (mainly used as animal feed), which leads to hypoxia and 'dead zones' in the coastal ecosystem. Biodiversity loss from eutrophication can also originate from the farm level where livestock concentration and the large amount of nutrient excreted pose a challenge for manure management (Carpenter et al. 1998). In mixed systems, there is an important biodiversity loss associated with the transition from natural to fertilized grasslands. Conversely, manure excreta in pastoral systems can have an important role for nutrient cycling and benefit biodiversity (Gibson, 2009).

Another type of pollution related to beef production arises from the use of ecotoxic substances. At the feed cultivation stage, the use of pesticide can have direct negative effects on non-target plant and arthropod species, and lead to a decline of species at higher trophic levels because their food resources are rarefied (e.g. birds). Arthropod species suffering higher mortality due to pesticides include pollinators, which could results in losses of agricultural production. At the animal husbandry stage, pollution by ecotoxic substance can result from the use of veterinary products (e.g. antibiotics, anthelmintics, hormones) These substance can have an effect on aquatic and soil biodiversity, as well as on insects and scavenger species (Boxall et al., 2002).

Reciprocally, biodiversity can also have an influence on beef production. High plant species richness in grassland is correlated with higher biomass production, as well as carbon storage and resistance to weed invasions (Finn et al., 2013). Inter-specific differences in maturity and nutritive value also lead to a more stable digestibility of forage along the grazing season. In rangelands, biodiversity is important for the resilience of pastoralist systems as heterogeneous landscapes are able to provide resources in a wider range of climatic situations.

6. Discussion - managing environmental performance in the context of broader sustainability

The interactions between beef supply chains and the environment span over the entire spectrum of global environmental concerns and are specific to each production system. Table 3 provides a broad brush overview of these interactions. No production systems performs better than the others in absolute terms. Maintaining a diversity of systems in adequacy with the diversity of agri-environmental conditions and societal needs, identifying specific interactions, risks and opportunities as well as implementing the necessary improvements in each system will therefore be necessary.

Interventions that have been shown to improve livestock and environment interactions are numerous (Table 3). Strategies obviously need to be tailored to local conditions and constraints and the combination of several practices and technologies (i.e. technical packages) is often required to achieve significant improvement (Mottet et al., forthcoming). One may however recognize three major principles for interventions.

First, aim for improved natural resource use efficiency, defined as the amount of natural resources engaged per unit of product. This is an objective of global relevance, which applies to the most affluent areas of the globe, where the sector is requested to minimize its environmental impact, and to emerging economies, where livestock production expands rapidly in a context of relatively weak environmental policies and often wastes natural resources. It is equally relevant to the poorest regions of the world, but from an opposite perspective: here, there is a need for maximizing production out of limited resources (Gerber et al. 2014).

Second, tap into the substantial improvement potential that lies in the heterogeneity of environmental performance among production units, even within production systems. As documented by Thoma et al. (2013) for US dairy farms, the large diversity of management practices and technologies used on production units translates in significant differences in environmental impacts. There is thus an important potential to improve the environmental performance of the sector by fostering the wider adoption of best practices and thus narrowing the environmental performance gap. Gerber et al. 2103 modelled that such approach could reduce global livestock GHG emissions intensity by about one third.

Third, the need to focus continuous improvement, acknowledging that environmental sustainability is a relative state, which depends on the overall level of human activities, on the status of resources and availability of technologies. This principle is also powerful in providing development pathways for all producers and stakeholders along supply chains, irrespectively of their initial practices. Guiding continuous improvement however requires to be equipped with fair and accepted indicators. Here is a clear role for science, to generate metrics and methods to monitor and benchmark environmental performance on a range of issues.

A particular challenge to sustainability of beef supply chains is the existence of multiple trade-offs between environmental interactions. This is further complicated by the large range of other sustainability challenges that the sector faces, rooted in issues such as public health (diets, food safety and antimicrobial resistance), food security, equity, economic growth and animal welfare. These elements often closely relate to environmental interactions and need to be addressed in a comprehensive way.

When addressing the environmental performance of livestock production, it is essential to keep in mind the ultimate needs of society that are met by the system in question: the roles played by cattle are particularly wide-ranging and beyond just providing food. Science is a key to identifying solutions to mitigate these trade-offs, i.e. to make improvements on one dimension at lower costs on other dimensions. In parallel to science, there is a need for constructive dialogue towards an agreement on the relative priority given to these competitive goals. Science based dialogue is essential to the development of effective policies and practice change. Examples of processes facilitating such kind of dialogue are the Global Agenda for Sustainable Livestock (http://www.livestockdialogue.org) and the Global Round Table for Sustainable Beef (http://grsbeef.org).

Table 3. Summary of major environmental interactions and improvement opportunities

Environmental categories	Pastoral		Mixed		Industrial	
	Interactions	Opportunities for improvement	Interactions	Opportunities for improvement	Interactions	Opportunities for improvement
Land and water (feed)	(-) Large occupancy, possible degradation. (+) Management in open spaces allowing multiple usages. (+/-) Animal trampling.	Improved range and pasture management, e.g. through mobility, rotational grazing, etc. Development of feeding operation in integration with cropping areas (crop residues and by-products). General productivity gains where possible (animal health, feed supplementation, genetics).	(+) Use of crop co-products and improvement of agricultural productivity, which result in higher land use efficiency.	Feed ration balancing, feed supplementation and animal health improvement to increase feed conversion.	(-) Competition with food production. (-) Withdrawals and water pollution related. (+) Use of agricultural co- and by-products.	Precision agriculture to minimize water usage and water pollution. Precision feeding, animal health and animal management to improve feed conversion.
Nutrient cycles	(+/-) Fertility transfers from grazing areas to manure deposition area.	None in particular.	(+) Fertilization.	Improve manure collection rates as well as processing and recycling to limit losses (including gaseous).	(+/-) Fertilization/pollution.	Manure collection, processing and management to minimize pollution. Precision agriculture on feed crops to optimize nutrient use efficiency.
GHG emissions	(-) Relatively high GHG emissions per unit of product.	Legume introduction in pasture. Improved range and pasture management, e.g. through mobility, rotational grazing, etc. Control of land conversion, and especially of feed-crop and pasture into natural habitats. General productivity gains where possible (animal health, feed supplementation, genetics).	(+/-) Moderate to low GHG emissions per unit of product.	Feed ration balancing, feed supplementation and animal health improvement to reduce emission intensities. Where possible, reduction of age at first calving and of breeding overhead to reduce emission intensities.	(+) Relatively low GHG emissions per unit of product.	Improve energy use efficiency, e.g. farm equipment and transport. Manure management and processing.
Biodiversity	(-) Overgrazing and land degradation. (+) Habitat creation and maintenance.	Range management compatible with biodiversity (open spaces). Improved range and pasture management to avoid land degradation, e.g. through mobility, rotational grazing, etc.	(-) Grassland abandonment or intensification.	Land use planning to maintain a mosaic of agro-ecosystems Manure management and Integrated Pest Management to avoid potential detrimental effects of intensification.	(-) Nutrient & pesticides pollution.	Precision agriculture to minimize water usage and water pollution. Precision feeding, animal health and animal management to improve feed conversion and thus spare land for conservation.

Source: compiled from Bignal & McCracken (1996); Capper (2012); Castillo et al. (2000); Ewers et al. (2009); Finn et al. (2013);Foley et al. (20011) ; Gerber et al. (2013); Herrero et al. (2013); Menzi et al. (2010); Oenema (2005), Opio et al. (2013); Steinfeld et al. (2006); Sutton et al. (2013); Tilman et al. (2002).

Table 4 proposes a simplified overview of these challenges and opportunities, and how they translate into different entry points and opportunities for intervention aiming at increased environmental sustainability.

In pastoral systems, environmental impacts per unit of product are generally high but absolute impacts are low because of the small production volumes. Livestock is the main asset communities can rely on to live in harsh environments characterised by an erratic biomass production. Capacity to innovate is limited by the prime obligation of resilience and the need to avoid risks inherent to any practice change. In these conditions, environmental outcomes can hardly be prime objectives in themselves. Sustainable natural resources management should be addressed as means to productivity and resilience, and environmental outcomes as co-benefit.

Feedlots, on the contrary, serve the middle class consumers in urban area. They mostly developed as an effective way to respond to a demand for beef expressed by a food secure population. Environmental impacts are moderate per unit of product but high in absolute terms, especially given the geographical concentration. Given such impacts, the limited contribution to food security and the strong capacity of feedlot operators to invest and innovate, environmental outcomes may well be sought as objectives in their own right. Furthermore, given the strong growth of these systems, impact intensity should be addressed in combination with overall impacts to avoid missing aggregated effects.

In-between, beef production in mixed systems (including dairy and beef herds) have generally lower environmental impact intensity but a large overall impact given the sheer size of the cattle population in these systems. Livestock is integrated with crops and contributes to agricultural productivity and diversification. Poor resource use efficiency is however a constraint to productivity and environmental performance. Improving efficiency is thus a key entry point and an incentive for change.

This review confirmed the significant contribution the beef sector currently makes to environmental issues, but also its critical role in the development of sustainable food systems. It identified practical improvements that can improve environmental sustainability and highlighted the need to disentangle the diversity of beef supply chains and understand them in their specific functions and context to design appropriate interventions. To be sustainable, the sector needs to respond to the growing demand for livestock products and enhance its contribution to food and nutritional security; provide secure livelihoods and economic opportunities for hundreds of millions of pastoralists and smallholder farmers; use natural resources efficiently, address climate change and mitigate other environmental impacts; and enhance human, animal, and environmental health and welfare. Consequently, policy and management interventions need to best reconcile the various demands concerning productivity, sustainability and societal values, for now and the future, and they should be tailored to regional/national specificities.

Table 4. Overview of context, issues and options in addressing environmental interactions in beef production systems

	Pastoral	Mixed	Feedlots
Goods and services provided	Vast range, including: food, transport, traction, fibber, insurance, banking.	Several products, including: food, manure and traction	Meet and slaughter by-products
Contribution to food security	Essential	Important, through animal products and contribution to agriculture productivity	Limited; risk of food/feed competition; issues of over consumption
Contribution to rural economy	Direct (animal products), and indirect through transport and banking	Mostly direct (animal products)	Mostly through income but limited given relatively low labour requirements and vertical integration
Main environmental impacts (associated improvement options)	Land degradation may be an issue (maintain mobility, range management, distribution of boreholes). Can have positive outcomes on biodiversity water cycles and nutrient cycles.	None in particular. Can have positive outcomes on biodiversity water cycles and nutrient cycles. Depends on management	Manure management (gaseous emissions and leaching), intensive feed production
Producers capacity to react and invest	Traditional capacity to adapt but strongly constrained by resilience imperative (buffering), access to information, technology and financial resources	Constrained by access to information and financial resources	High
Exposure (sensitivity) to climate change	Very high (very high)	High (moderate: mitigated through diversification)	Moderate (high through input and output prices)
Cost of reaching out to producers and monitoring change	Very high because of dispersal, poor infrastructure and lack of baseline information	High because of size and dispersal of holdings.	Relatively low (large scale, geographical concentration)
General public perception	Generally positive in affluent country, often negative locally, among sedentary populations.	Generally positive	Generally negative (environmental impacts, animal welfare, growth promoters)

Entry points for public policies aiming at improving environmental performance	Natural resource management (range and water) for resilience, food security and poverty reduction is key. Environmental outcomes are "co-benefits"	Focus on productivity and natural resource use efficiency gains, given the positive effects on both food security and environmental outcomes	Improving environmental performance is an objective in itself. Size and geographical concentration of operations are key issue.

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FIGURE CAPPTIONS

Figure 1. Main features of digestive systems among dominant livestock species. After Smil (2002)

Figure 2: Estimated cattle population in Grazing, mixed and feedlots systems. Source: GLEAM (Gerber et al., 2013)

Figure 3: Estimated composition of the global feed ration of cattle (In dry matter equivalent, beef and dairy herds included)

Figures 4. Regional comparison of the partitioning of energy requirements for dairy herd (up) and beef herd (down). Source: Opio et al. (2013). NENA: Near East and North Africa, LAC: Latin America and Caribbean, SSA: Sub-Saharan Africa.

Figure 5: Land use for producing beef protein. Land use is computed based on the beef herd intake and not on the actual land occupation GLEAM (Gerber et al., 2013).

Figure 6: Proportion of feed N retained in edible products: dairy herd (up) and beef herd (down)

Figure 7: Percentage of N and P in feed recovered in edible products, at animal level. Source: Gerber et al. (2014)

Figure 8: Global GHG emission intensities by commodity. Source: Gerber et al. (2013)

FIGURES

Figure 1

Presentation1.pptx

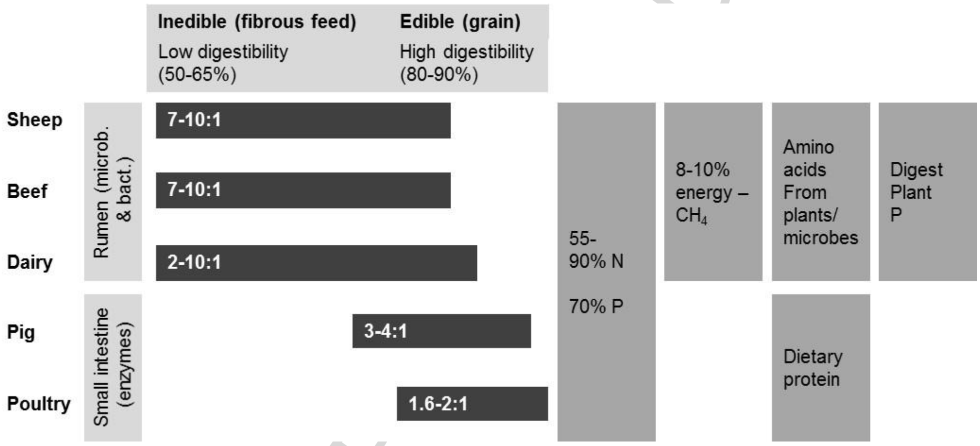


Figure 2

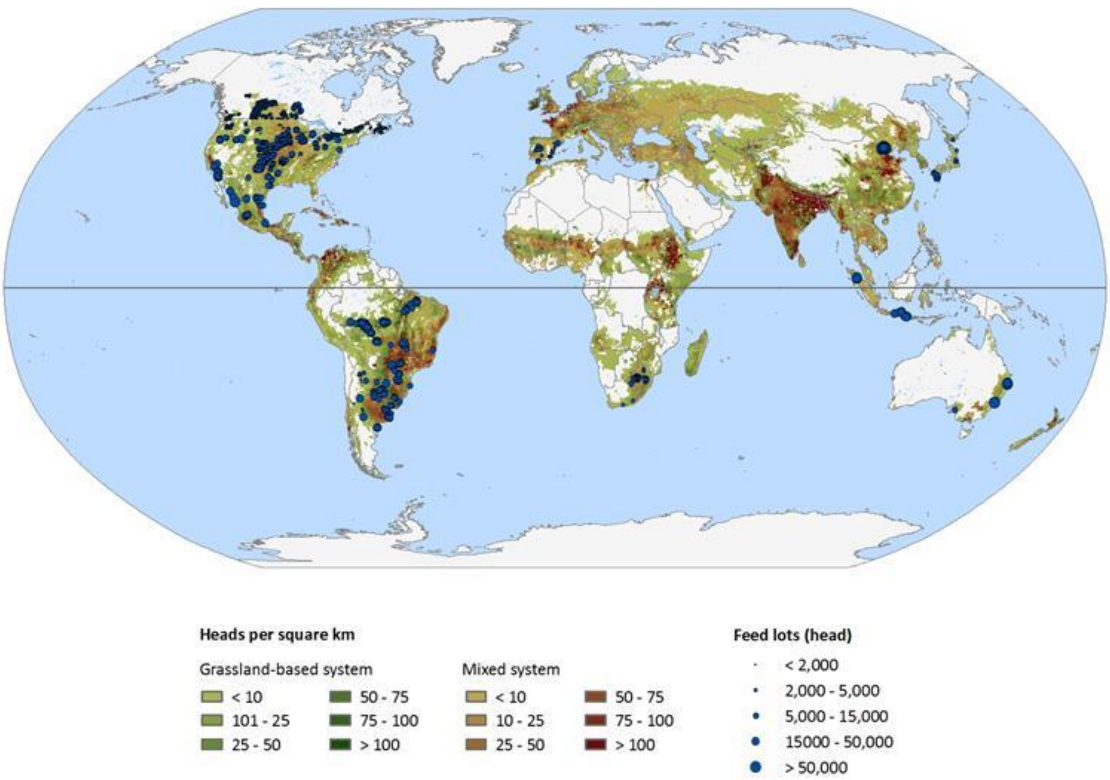

Heads per square km
Grassland-based system
< 10
101 - 25
25 - 50
50 - 75
75 - 100
> 100
Mixed system
< 10
10 - 25
25 - 50
50 - 75
75 - 100
> 100
Feed lots (head)
< 2,000
2,000 - 5,000
5,000 - 15,000
15000 - 50,000
> 50,000

Figure 3

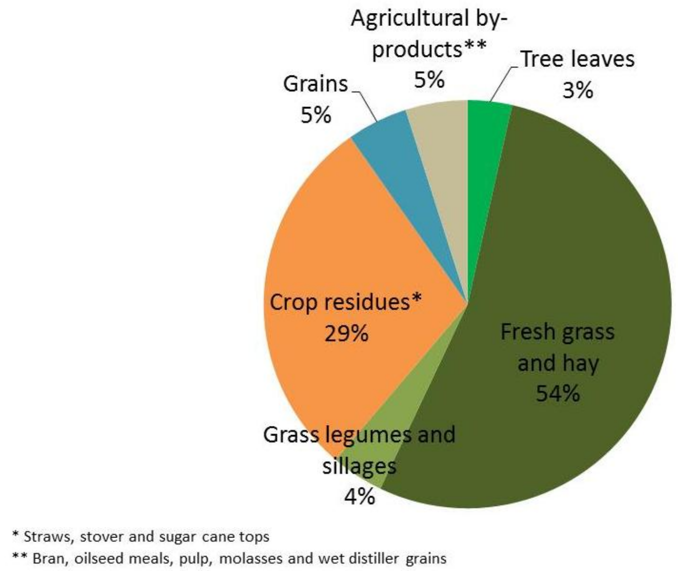

Agricultural by-
products**
5%
Tree leaves
3%
Grains
5%
Crop residues*
29%
Fresh grass
and hay
54%
Grass legumes and
sillages
4%
* Straws, stover and sugar cane tops
** Bran, oilseed meals, pulp, molasses and wet distiller grains

Figure 4

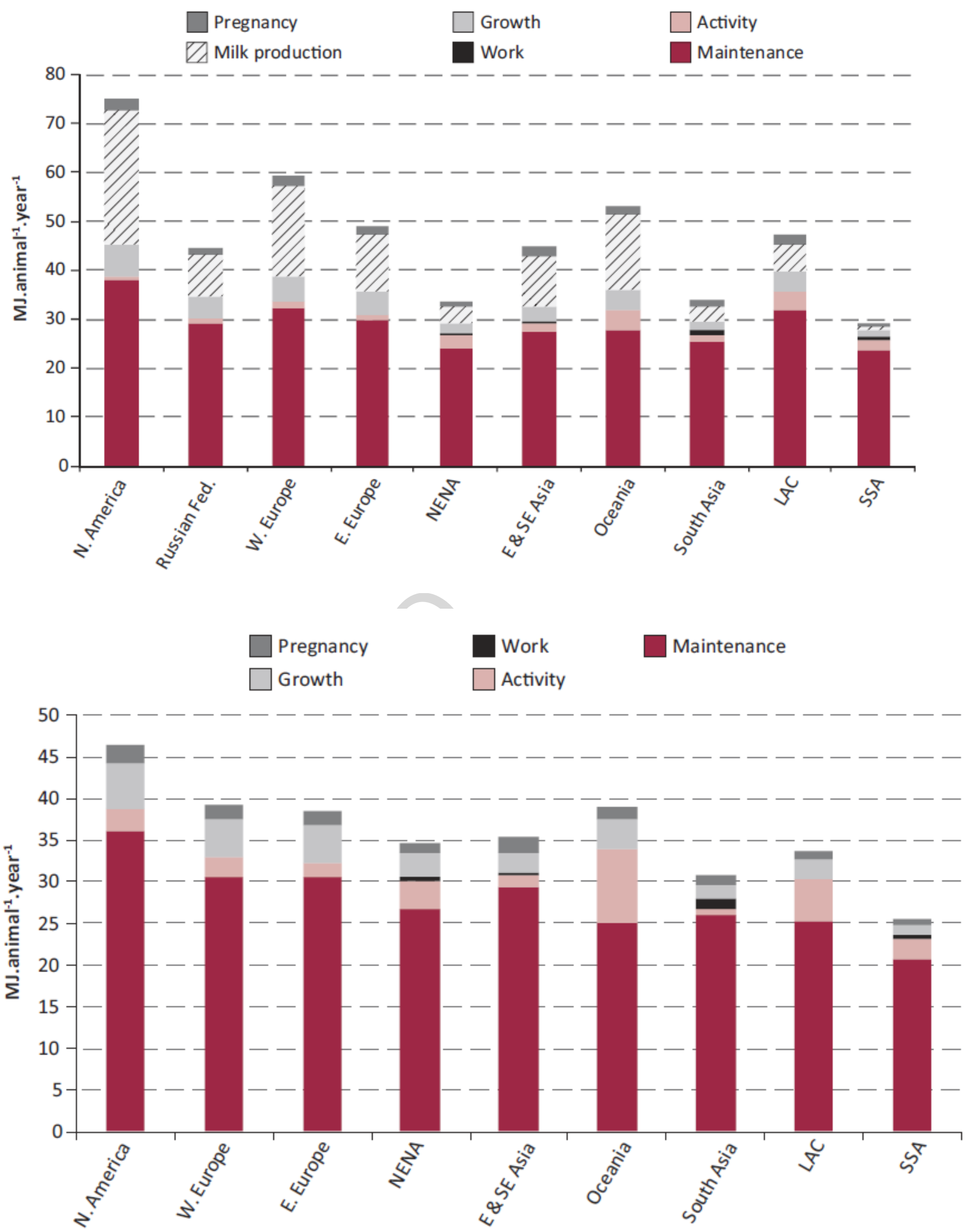
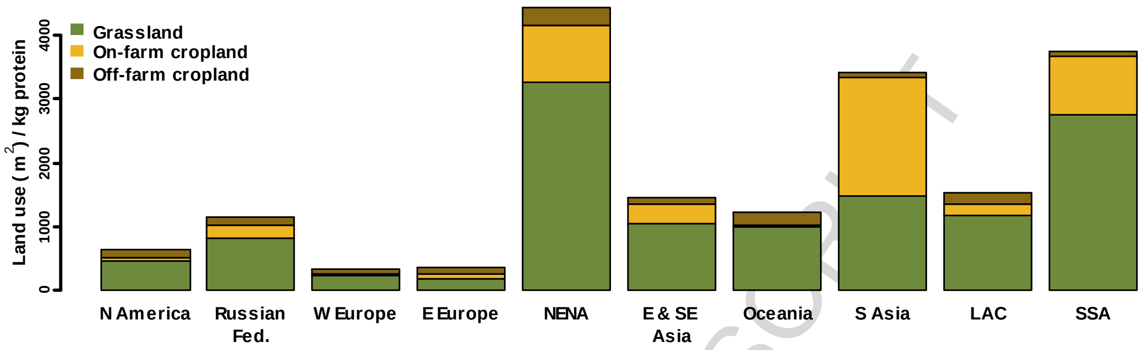
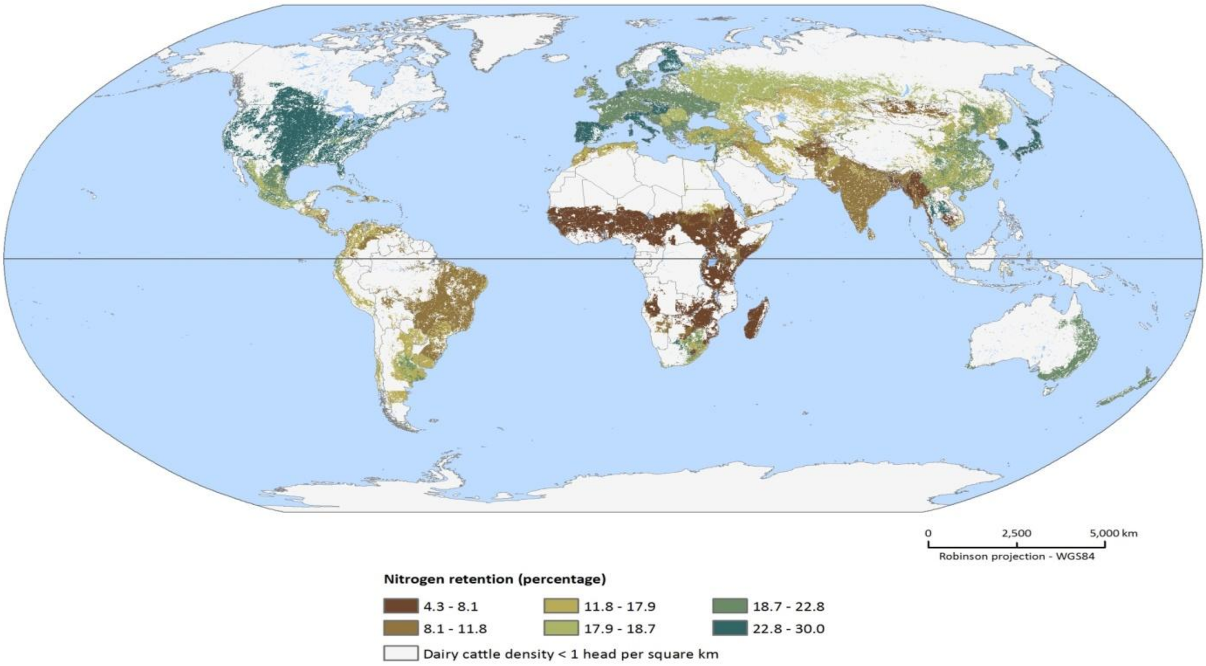

Pregnancy
Growth
Activity
Milk production
Work
Maintenance
MJ.animal⁻¹.year⁻¹
0
10
20
30
40
50
60
70
80
N. America
Russian Fed.
W. Europe
E. Europe
NENA
E & SE Asia
Oceania
South Asia
LAC
SSA
Pregnancy
Work
Maintenance
Growth
Activity
MJ.animal⁻¹.year⁻¹
0
5
10
15
20
25
30
35
40
45
50
N. America
W. Europe
E. Europe
NENA
E & SE Asia
Oceania
South Asia
LAC
SSA

Figure 5



[See legend of Fig. 4 for region names.]

Figure 6


0
2,500
5,000 km
Robinson projection - WGS84
Nitrogen retention (percentage)
4.3 - 8.1
8.1 - 11.8
11.8 - 17.9
17.9 - 18.7
18.7 - 22.8
22.8 - 30.0
Dairy cattle density < 1 head per square km

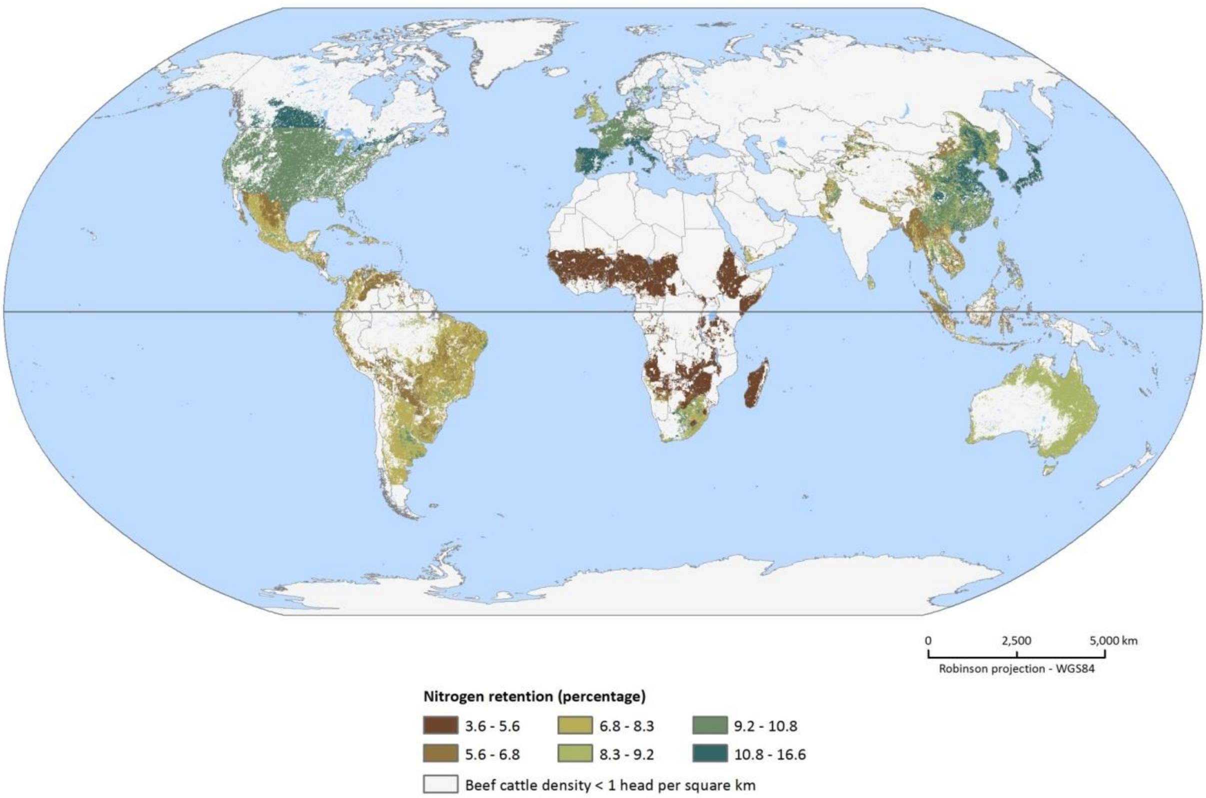

0
2,500
5,000 km
Robinson projection - WGS84
Nitrogen retention (percentage)
3.6 - 5.6
5.6 - 6.8
6.8 - 8.3
8.3 - 9.2
9.2 - 10.8
10.8 - 16.6
Beef cattle density < 1 head per square km

Figure 7

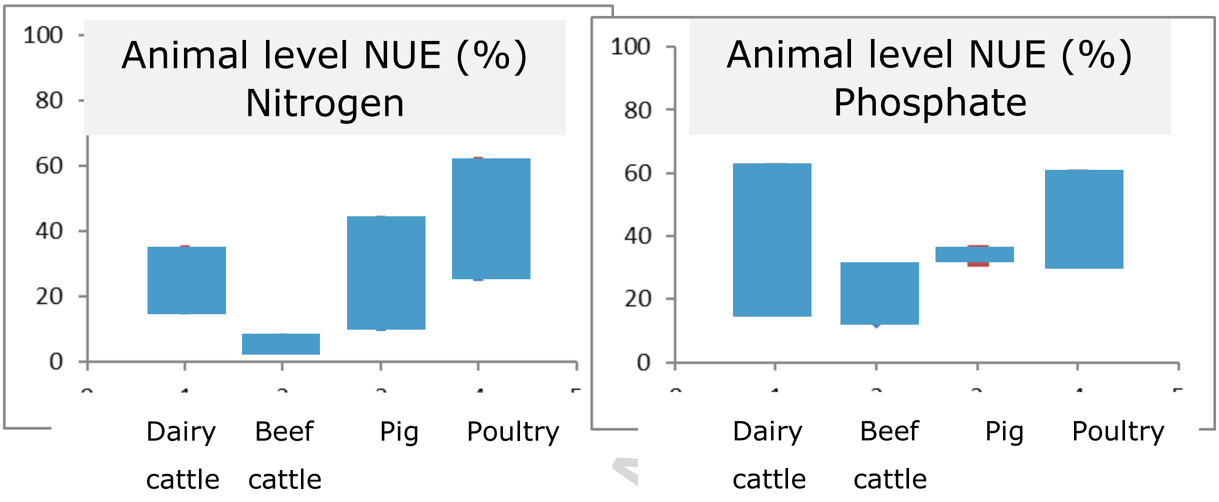
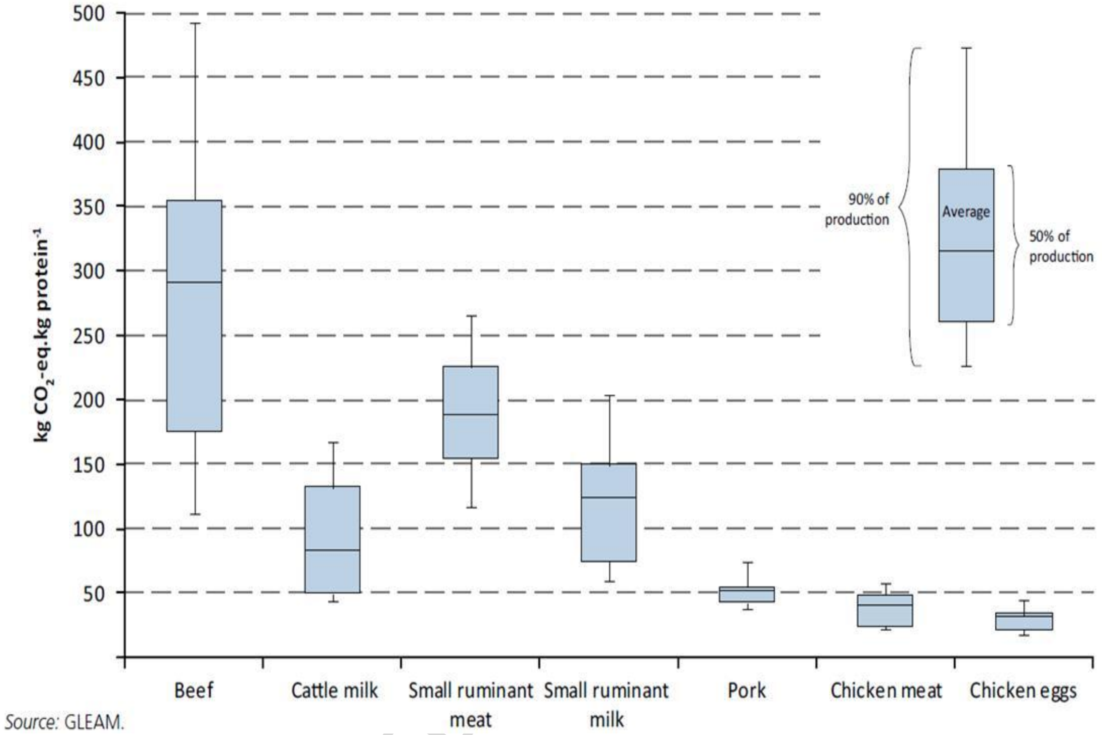

Animal level NUE (%)
Nitrogen
100
80
60
40
20
0
Dairy cattle
Beef cattle
Pig
Poultry
Animal level NUE (%)
Phosphate
100
80
60
40
20
0
Dairy cattle
Beef cattle
Pig
Poultry

Figure 8


500
450
400
350
300
250
200
150
100
50
kg CO2-eq.kg protein-1
90% of production
Average
50% of production
Beef
Cattle milk
Small ruminant meat
Small ruminant milk
Pork
Chicken meat
Chicken eggs
Source: GLEAM.

Highlights:

- Beef often has a greater impact per unit of output than other animal commodities.
- Large diversity in production systems, producing a range of goods and services.
- Cattle is the main option to sustain communities in harsh climatic conditions.
- Environmental interventions need to address diversity and broad development issues.
- Resilience, efficiency and net impacts are key entry points in pastoral, mixed and feedlots systems, respectively.