Toward the inclusion of environmental considerations in Livestock Master Plans

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Livestock and Climate

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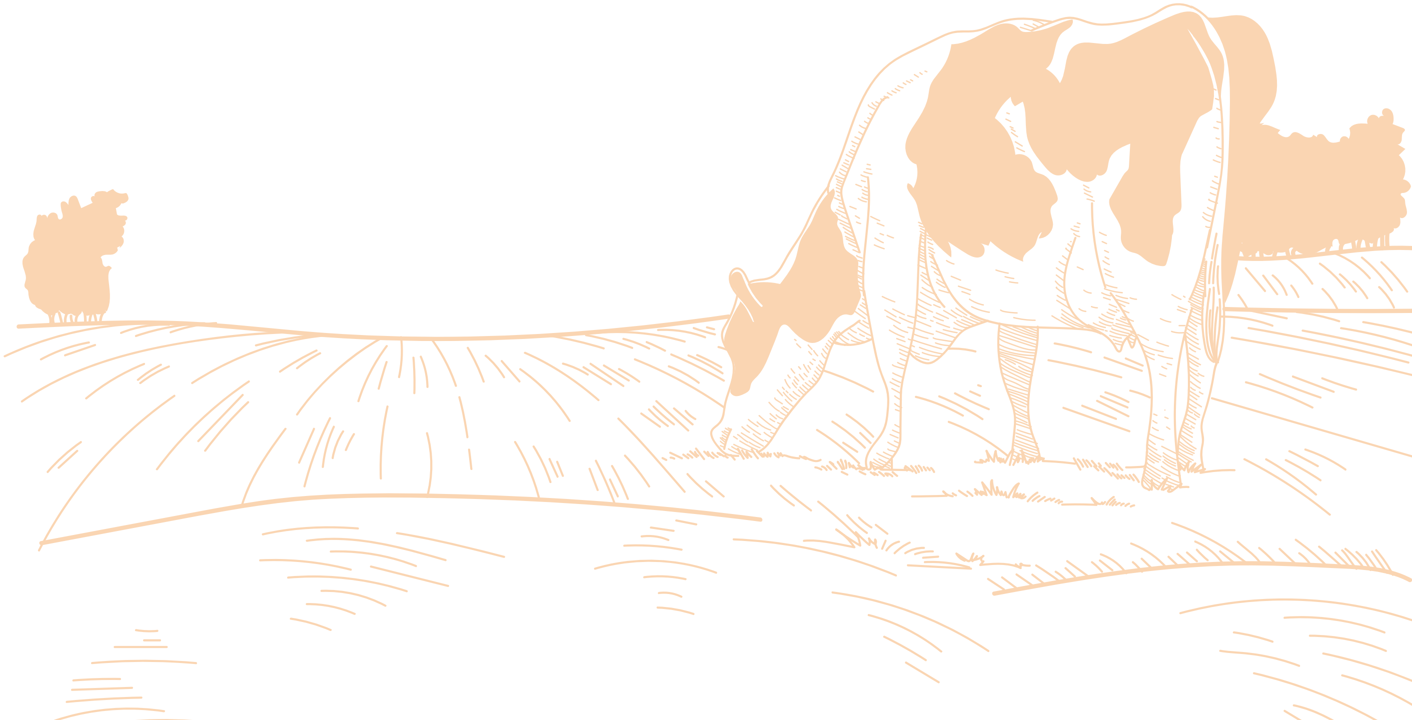

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1.1 Introduction

To meet future global demand for food, the productivity of food systems will need to increase, land and other natural resources will need to be used more sustainably, and negative impacts on the environment will need to be minimized while opportunities are sought to restore lands that have already lost nutrients and/or biodiversity (Herrero et al., 2021). The livestock sector plays a key role in fulfilling human food needs because it provides high amounts of protein and micronutrients per unit of product (Herrero et al., 2021). In developing countries, livestock systems substantially contribute to increasing livelihood resilience for many smallholders and offer ways to lift people out of poverty by providing regular income and employment (World Bank, 2009). In addition, these systems provide other benefits to society, such as traction, soil nutrients from manure, and risk management (Havlík et al., 2014; Mehrabi et al., 2020; Thornton and Herrero, 2010). In recent decades, livestock have been one of the fastest-growing agricultural subsectors, driven by the growing demand for livestock products because of population growth, higher income, and urbanization in developing countries (Herrero et al., 2021; Thornton, 2010). Because of this, along with natural resource use, environmental impacts from livestock have increased, making this sector an important contributor to climate change; nutrient mining; water, energy, and land use; biodiversity loss; and pollution of water streams and soils, among other negative environmental impacts. Therefore, reductions in environmental burdens and sustainable natural resource use by the livestock sector will be necessary as production increases to meet future food demand.

A substantial part of the environmental impacts and natural resource uses attributed to the agricultural value chain is associated with animal feed production. Regarding greenhouse gas (GHG) emissions from the agricultural sector, feed production systems contribute more than 60% (Mogensen et al., 2014). Confirming the above, several studies have reported that feed production is one of the most environmentally damaging processes within the agricultural sector, specifically in livestock production (Groen et al., 2016; Mogensen et al., 2014; Niero et al., 2015; Noya et al., 2018). In most cases, these contributions arise from the cultivation of feedstuffs such as pastures, maize, wheat, barley, sorghum, soy, and oats, among others, that are usually included in animal diets (Groen et al., 2016; Mogensen et al., 2014; Nguyen et al., 2010; Noya et al., 2018). Some studies have reported that future improvements in livestock yields (animals and crops) are not enough to meet expected demand for animal source food by the global population (Hayek et al., 2020; Sitters et al., 2020). Therefore, additional land will be necessary for livestock systems to fulfill future feed demand, which would lead to land-use changes, biodiversity losses, additional natural resource use (water and nutrients), and possibly damaging environmental impacts. Considering this, seeking sustainable ways of production would help to mitigate the environmental impacts and lead to more efficient use of inputs and natural resources by livestock systems (Havlík et al., 2014). This could be achieved through better feeding practices that include better quality feed, higher crop and pasture yields, improved animal breeding, reproductive efficiency and health interventions, and improved grassland management (Gill et al., 2010; Havlík et al., 2014; Thornton and Herrero, 2010). Such practices would lead to transitions from low-input low-output systems (i.e., extensive rangeland systems) to more efficient and productive livestock systems (i.e., mixed crop-livestock and intensive livestock systems).

Interventions in the livestock sector have different outcomes regarding environmental behavior and natural resource use, which are not always synergistic with productivity increases, increased income, or human welfare (Notenbaert et al., 2020). In addition, many trade-offs exist among the environmental impacts evaluated in livestock systems. Therefore, it is a challenge to balance livestock production, environmental protection, and livelihoods (Thornton and Herrero, 2010). Considering this, policymakers and decision-makers at different levels need information about the trade-offs and synergies of the final outcomes of livestock interventions.

Table 1 displays preliminary observations on the environmental impacts associated with different livestock production systems: ruminant species and monogastrics. This table allows the identification of the main environmental impacts associated with the level of production intensity and is a guide to establishing the baseline of the environmental behavior of livestock systems as well as the intervention scenarios to minimize the environmental impacts and increase animal and crop yields.

Table 1. Major environmental impacts of different production systems. Adapted from Raney et al. (2009).

Environmental impacts	Ruminant species (cattle, sheep, goats)		Monogastrics (pigs, poultry)	
	Extensive grazing systems	Intensive grazing systems	Traditional systems	Industrial systems
Greenhouse gas emissions				
Feed production				
CO_2 emissions from land-use and land-use change for grazing and feed-crop production	Negative	Negative	Not significant	Negative
CO_2 emissions from energy and input use	Not significant	Negative	Not significant	Negative
Carbon sequestration in rangelands	Positive	Positive*	Not significant	Not significant
Animal herd				
Methane emissions from digestion	Negative	Negative	Not significant	Not significant
Nitrous oxide from manure	Negative	Negative	Not significant	Negative
Land occupation				
Feed production				
Crops and pastures production processes	Negative	Negative	Negative	Negative
Animal herd				
Grazing activities	Negative	Negative	Not significant	Not significant
Confinement	Not significant	Negative	Not significant	Negative
Eutrophication				
Feed production				
Land fertilization	Not significant	Negative	Negative	Negative
Animal herd				
Excreta management	Not significant	Negative	Not significant	Negative
Acidification				
Feed production				
Land fertilization	Not significant	Negative	Not significant	Negative
Animal herd				
Excreta management	Not significant	Negative	Negative	Negative
Water use				
Feed production				
Crops and pastures production processes	Negative	Negative	Negative	Negative
Animal herd				
Maintenance of facilities	Not significant	Negative	Not significant	Negative
Animal consumption	Not significant	Not significant	Not significant	Not significant
Biodiversity				
Feed production				
Habitat destruction from feed-crop production	Negative	Negative	Not significant	Negative
Expansion into natural habitat	Negative	Negative	Not significant	Negative
Ecosystem maintenance	Positive	Positive*	Not significant	Not significant
Animal herd				
Habitat destruction from animal wastes	Negative	Negative	Not significant	Negative
Ecosystem maintenance	Positive	Positive*	Not significant	Not significant

** Can be positive dependig on the management practices*

Negative inpact with lower affectation

Negative inpact with higher affectation

A Livestock Master Plan (LMP) is a five-year sector investment plan and includes both investment analysis and a budget — both a financial and a human resource budget — that guide the development of a country's sustainable livestock sector (Staal et al., 2022). It aims to affect the economy of the country in which it is developed and to accomplish the development objectives of the people and government. These include reducing poverty, increasing the revenue that the sector contributes to either state or national income, and improving food and nutrition security by including a strategy to increase animal source food consumption and exports (Staal et al., 2022).

LMPs provide a sector analysis that reflects the current situation, with a predictive analysis needed to set long-term strategies and design action plans. They enable a country to identify key livestock value chains and to develop production systems within each. Roadmaps with specific visions, targets, challenges, strategies, and proposed investments in technology and policy interventions, with expected outputs, outcomes, and impacts, are mapped out (Staal et al., 2022).

A Livestock Master Plan provides government policymakers, private investors, and development partners with reliable quantitative information on the current contributions and constraints of the livestock sector; the potential of the sector to contribute to national development objectives; priority livestock commodities and value chains, and proposed investment options (combined technologies and policies); and projections of how better-targeted investment in livestock can improve economic performance and improve lives in the sector (Staal et al., 2022). Although the investment options (intervention scenarios) are expected to be evaluated economically and productively, the environmental impact calculations are still missing in LMPs.

Therefore, this document intends to guide the inclusion of environmental considerations in the development of LMPs and, as such, contributes to the planning of more sustainable interventions in the livestock sector. It identifies the most pertinent environmental dimensions to consider, describes the main drivers of environmental impacts, and introduces the inputs, variables, and feedback loops to consider in LMP-supporting modeling efforts. In addition, it draws attention to the potential impacts of global climate and environmental change on livestock sector development and points to potential approaches to including climate change scenarios in LMP analyses.

UNIT 2

Livestock and the environment: Main interactions

2.1 Introduction

The production, transportation, processing, marketing, and consumption of animal source foods (ASF) are associated with a variety of environmental impacts. Most through-chain studies estimate that on-farm activities are the biggest contributor to environmental impact (FAO, 2016a, 2016b; Opio et al., 2013). In the following sections, we focus mostly on the impacts from on-farm production. It is thereby important to point out that, depending on the local context, technology, and management system, different impacts on the environment can occur. In addition, the importance, size, and urgency of the different impacts can vary hugely depending on the locally specific context. In the sections below, the main livestock-environment interactions are described in general terms. Section 3 then specifies how to estimate these different impacts in the context of a specific livestock production system within a country-level LMP.

It should be noted, however, that post-farm-gate activities – especially in developing countries – are often not very efficient, and impacts might generally be underestimated. The key resources used for meat and milk processing are water, raw materials, and energy. Processing often produces blood by-products and waste streams, while the facilities are also prone to disease spread. In addition, the problem of food waste related to livestock-derived food products deserves considerable attention. The United Nations (https://news.un.org/en/story/2013/09/448652) estimates that roughly one-third of the food produced in the world becomes lost or wasted. This leads to a major squandering of resources, including water, land, and energy used in their production, and needlessly produces GHG emissions.

Climate change is defined as the change in global climate patterns due to increases in global carbon emission rates as a result of the consumption of fossil fuels and anthropogenic activities that disrupt the carbon cycle, thus leading to warming the planet by increasing temperatures in the air and ocean (Ali et al., 2020). Although it is expected that global demand for livestock products will increase 100% by 2050, it is also known that climate change is affecting livestock production globally through competition for natural resources, biodiversity loss, heat stress, livestock diseases, and quality and quantity of feed (Garnett, 2009). Therefore, interest is growing in understanding the interaction of climate change and livestock production, and the real challenge is to keep a balance and identify synergies and trade-offs among food security, livestock productivity, and environmental preservation (Rojas-Downing et al., 2017; Wright et al., 2012).

2.2 Livestock as users of land and water

Livestock systems are one of the main users of land. Steinfeld et al. (2006) estimated that livestock globally use 3.4 billion hectares for grazing and 0.5 million hectares of cropland to produce feed (33% of arable land). Of the grazing areas, 2.3 million hectares (67%) are in the developing world. The expansion of pastureland at the expense of natural habitats in the developing world has been on the order of 330 million hectares from 1961 to 2007in the last 40 years (FAO, 2009). This phenomenon has occurred predominantly in Latin America and is projected to increase by a further 100 to 120 million hectares by 2050 under current practices (Smith et al., 2010). Cropland area in the same period expanded by 190 million hectares and is expected to increase at a faster rate than rangelands to supply additional feed for monogastric production and more intensive ruminant production (Smith et al., 2010), which will require an additional 450 million tons of grain to meet human demand for animal products by 2050 (Rosegrant et al., 2009). Fuglie et al. (2021) estimate that cultivated forage crops are planted on at least 159 million hectares (compared to 167 million ha of rice).

Land use is closely linked to water cycles. Not surprisingly, 90% of the water used by livestock is through the effects of grazing and producing feed. The fraction of drinking water accounts for less than 10% of the total (Peden et al., 2007). Recent research (Heinke et al., 2020) suggests that, globally, feed production for the livestock sector appropriates 5.315 km^3 per year of evapotranspiration (9% of global evapotranspiration). The authors found that feed production from croplands uses 37% of the water for crop production and the biomass consumed by livestock from grazing lands appropriates 32% of the total evapotranspiration (ET) from grazing lands. The rest of the ET supports a provision of a range of ecosystem services, a key role that rangelands are playing globally. Enhancing this role through improved rangeland management could be essential for enhancing global green water cycles (Rockström et al., 2007). At the global level, the aggregated virtual water content (VWC) of livestock products has an average value of 5.63 m^3 per 1,000 kcal. In contrast, the VWC of vegetal products from croplands is estimated to be only 0.66 m^3 per 1,000 kcal (Heinke et al., 2020). Producing livestock products used, on average, nine times the amount of water that it takes to produce calories from crop-based products. In their study, total VWC for individual products ranged from 1.50 m^3 per 1,000 kcal for pig meat up to 35.24 m^3 per 1,000 kcal for meat from dairy sheep and goats, with the range reflecting vast differences in intensity of production (feed, agro-ecology, species, type of production system, and others). Green water represented 97% of the water used by livestock (Heinke et al., 2020).

2.3 Livestock as emitters of greenhouse gasses

Livestock systems are an important contributor to global GHG emissions. Current estimates range from 8% to 18% of global anthropogenic GHG emissions (Gerber et al., 2010, 2013; Goodland and Anhang, 2009; Herrero et al., 2011; O'Mmara, 2011; Sarkwa et al., 2016; Steinfeld et al., 2006; Adegbeye et al., 2020), with the range reflecting methodological differences (inventories vs. life cycle assessment), attribution of emissions to land use (Herrero et al., 2011; O'Mmara, 2011), and uncertainty in parameter values (Gerber et al., 2010). According to Gerber et al. (2013), methane (CH4) from enteric fermentation, nitrous oxide (N2O) from manure management, and carbon dioxide (CO2) from land use contribute 44%, 29%, and 27% to the emissions of the livestock sector, respectively. Livestock in the developing world contribute about 60% of the total emissions from livestock globally (FAO, 2019a). Emission intensities also vary with differences mainly related to the species (monogastrics are more efficient than ruminants), products (milk, white meat, and eggs are more GHG efficient than red meat), and the productivity of the animals (the higher the productivity, the lower the emissions per unit of product) (Gerber et al., 2013). These aspects are largely dependent on feed type, quantity, quality, and provenance and the manure management system implemented. The amount of the GHG emissions from manure depends mainly on collection and storage management as well as N-level excretions and weather conditions. Large heterogeneity exists in emission intensities in the developing world (Gerber et al., 2013). However, in general terms, the following order usually prevails: industrial systems are less GHG intensive and these are followed by mixed crop-livestock systems and by grazing systems (Gerber et al., 2013). A recent study by Ndung'u et al. (2022), however, finds that the GHG emission intensities of low-intensity African livestock systems are not as high as believed and, in the region, are exemplars of traditional smallholder cattle farms showing that low-carbon farming is present in extant operations. In addition, smallholder cattle farms have great mitigation potential, without the need for industrial-style intensification (Ndung'u et al., 2022). Emission intensities of systems in temperate tropical highlands are usually lower than in drier areas (Gerber et al., 2010). Nevertheless, livestock systems, in general terms, generate significantly more emissions per kilocalorie than crops. However, the mitigation potential in the livestock production sector by 2030 is projected to be very large (1.74 Gt CO2-eq per year), with land-use management practices (carbon sequestration in rangelands, land-sparing impacts of reduced animal numbers/production intensification) representing more than 80% of this potential (Smith, 2012; Smith et al., 2007b, 2007a). Most of the mitigation potential (70%) lies in the developing world (Herrero et al., 2016; Smith et al., 2007b).

2.4 Livestock as nutrient recyclers

Livestock have a different role in nutrient cycles in the developed-industrialized world and in the developing world. In Western Europe and North America, crops are mostly sustained on synthetic fertilizers and livestock production on the import of feed, sometimes produced thousands of miles away. In much of the industrialized world, the link between livestock and the land has been broken, with animals separated spatially from the places where their feed is produced (Naylor et al., 2005). The spatial decoupling of crop and livestock production is further associated with smaller fractions of manure returned to cropland and larger losses of manure N to surface water and groundwater and GHG emissions (Bai et al., 2018). In large parts of Africa and East and Southeast Asia, agricultural production and nutrient cycles are closely related to local-scale recycling of organic residues (including animal manure) (Herrero et al., 2013). In response to increasing demand for livestock products, these traditionally mixed systems increasingly become intensified and are thereby replaced by specialized livestock production systems with spatially decoupled crop and livestock production and high levels of resource depletion and/or environmental pollution (Garrett et al., 2017; Jin et al., 2020; Notenbaert et al., 2021). Meeting the increasing demand for animal protein in the developing world therefore requires managing nutrient cycles more efficiently (Herrero et al., 2013).

Livestock activities influence soil health positively and/or negatively, that is, excretions are an important source of nutrients and organic matter for soils in livestock systems in developing countries. Livestock manure – considered a serious problem in the developed world – is a critical agricultural resource in large parts of Africa, where soils are inherently poor (Herrero et al., 2013; Petersen et al., 2007; Rufino et al., 2007). The manure contributes from 12% to 24% of the nitrogen input in nitrogen cycles in cropland in the developing world (Liu et al., 2010). Recycling of animal manure is practiced in most mixed crop-livestock systems (Jin et al., 2020), although efficiencies are rarely close to those of the developed world (Rufino et al., 2007). Small-scale farmers depend on the low fertility of their soils to produce food crops and/or on livestock to concentrate nutrients from the grazing lands, mainly because synthetic fertilizers are unaffordable for most of them (Anang et al., 2021; Herrero et al., 2013). Because of non-optimal excreta management and limited fertilizer application in non-specialized livestock systems, located mainly in developing countries, considerable nutrient mining can be found in crops and pastures, which leads to nutrient imbalances (Garrett et al., 2017). Moreover, livestock trampling in overgrazed areas can lead to soil compaction and erosion, which could degrade the land and affect its productive parameters (Antoneli et al., 2018).

Intensifying livestock production requires using additional nutrients to produce feed (da Silva Cardoso et al., 2020; Herrero et al., 2013). In the developed-world dairy industry, nitrogen-fixing legumes play an important role, with soybeans produced in South America and the U.S. being fed as protein supplements in Europe (Herrero et al., 2013; Watson et al., 2017). Research in the developing world has tried to implement this model of using legumes produced on the farm on a local scale in, for example, African mixed systems, with some success (da Silva Cardoso et al., 2020; Sumberg, 2002), but not enough to meet the future demand for feed. Poverty has often been associated with poor soil fertility (Sanchez, 2002; Tsehai et al., 2016) and problems of fertility are often not solved by just adding fertilizer, but this requires a sensible use of organic resources (Chivenge et al., 2011; Nair, 2019). In many farming systems, food crop production is directly or indirectly related to livestock production. The direct relationship arises from the need for animal manure to increase the effectiveness of fertilizer applied to cropland (Vanlauwe and Giller, 2006). The indirect relationship arises from the competition for biomass to restore degraded agricultural soils or to feed growing livestock populations (Rufino et al., 2011).

Although animal manure can be an effective soil amendment, in systems where the land supports livestock production, its availability at the farm level is often quite limited. This implies that designing technologies for soil fertility restoration around only the use of animal manure is unrealistic (Herrero et al., 2013; Timsina, 2018). Bouwman et al. (2011), in a historical analysis of nutrient cycles, show that it was the introduction of synthetic fertilizers that allowed the explosive increase in livestock production globally. Agriculture based only on the recycling of organic resources and supported by N-fixing legumes could not have supported the current global production and consumption of animal protein (Herrero et al., 2013; Zhang et al., 2020). The widespread use of fertilizer has helped to intensify not only agricultural production but also the rate of nutrient cycling, with the accumulation of nutrients in certain environments creating threats to human health and nature (Sutton et al., 2011).

Nutrient balance is a useful tool for quantifying the flow of nutrients in agricultural systems (Cederberg and Mattsson, 2000), allowing the quantification of nutrient surpluses and, thus, the risk of leaching and runoff. Nutrient surplus is quantified as the difference between net nutrient output from the production system in products and coproducts and the net nutrient input to the farm (Dalgaard et al., 1998). Nutrient surpluses are usually low in low-input livestock systems (extensive and traditional), contrary to high-input systems (intensive and industrial), in which the surpluses used to be high. Nutrient surpluses are usually transmitted into different environmental impacts such as GHG emissions, freshwater eutrophication, and acidification of soils, among others.

2.5 Livestock and biodiversity

Biodiversity is essential for functioning ecosystems and refers to the variability among living organisms, including diversity at every level, from genetic to species, populations, and even ecosystems (United Nations, 1992). The concept indicates the levels of complexity and organization in ecological systems that, in various ways, determine the essential system functioning, such as productivity and responses to disturbances (Hooper et al., 2005). Maintaining this natural capital, with a portfolio of species, provides insurance that the system will be able to cope with disturbances and shocks, such as fires or pest outbreaks, and yet continue to provide desired ecosystem services, for example, feed crops, and, if damaged, rebuild and regain productivity. This capacity is particularly important today as we enter an era characterized by uncertainties related to the environment, such as the effects of climate change.

Five main drivers of biodiversity loss are recognized. These correspond to (i) habitat change, (ii) pollution, (iii) climate change, (iv) population growth, and (v) invasive species (Millennium Ecosystem Assessment, 2005). Livestock system management can influence positively or negatively most of these drivers, for example, global croplands for feed and pasture areas have expanded in recent decades, accompanied by large increases in natural resource use and inputs (energy, water, and fertilizer), resulting in biodiversity losses (Giam et al., 2015; Kreider et al., 2021; Raney et al., 2009). Land cover changes, such as the ongoing conversion of the Amazon rainforest to grazing lands or croplands for livestock, fundamentally degrade local biodiversity (Marengo et al., 2018; Nepstad et al., 2006). Further, heavy application of pesticides and fertilizers also results in losses of plant and animal species (Elmqvist et al., 2013) as well as secondary cascading effects on a larger scale, for example, destruction of coral reefs because of acidification of the ocean (Doney et al., 2009; Koop et al., 2001). In addition, intensification of livestock system production and overgrazing can lead to desertification, soil degradation, and preferential selection for invasive species, as it relies on a limited number of crop species and animal breeds. In contrast, extensively managed livestock systems on permanent semi-natural grasslands are among the habitats with the highest biodiversity levels, and large ruminant activities can contribute to enhanced biodiversity (Baldock et al., 1993; Claps et al., 2020; Metera et al., 2010; Teague et al., 2016). The on-farm feed production in livestock systems can be based on crops and/or grasslands, depending on the availability of natural resources, among other socioeconomic aspects (Moraine et al., 2017; Raney et al., 2009). Therefore, the feed regime is key to quantifying biodiversity (species diversity) as it defines the landscape and land-use characteristics of livestock systems.

It is important to remember that human development, especially during the past 300 years, has transformed almost all ice-free land surfaces into "anthromes" (anthropogenic biomes – human-shaped systems) and only 22% of areas remain as genuine wild lands (Ellis et al., 2010). A land-use change is thus often a change from one human-altered ecosystem to another (Paul and Rashid, 2017). Many livestock systems have evolved over long periods and many of these agricultural ecosystems have a high level of biodiversity (Sabatier et al., 2015). In Northern Europe, heavily managed landscapes as a result of livestock production today thus have an ecological as well as cultural value (Deutsch et al., 2011). Impacts on biodiversity are consequently not only negative. Livestock production can be used as a tool for maintaining and increasing biodiversity, from the African savannas to European meadows (Alkemade et al., 2013; Metera et al., 2010). Also, recent intensification has increased the productivity of livestock production (Godde et al., 2018). Thus, fewer land resources are required per kg of produced product, resulting in a decoupling of the linear relationship between production increases and environmental degradation (Notenbaert et al., 2014; Röös et al., 2017).

However, a huge knowledge gap remains on the link between biodiversity and the generation of multiple ecosystem services in relation to livestock production systems (Science for Environment Policy, 2015). There is a need to highlight and promote positive benefits as well as prevent and balance the significant and alarming impacts of livestock production on biodiversity.

2.6 The impact of global environmental change on livestock

Climate change – with its projections of rising temperatures and CO2 levels, changing rainfall patterns, and the likely increase in climate variability and occurrence of extreme events – causes major impacts on livestock and on the ecosystem goods and services on which they depend (Vermeulen et al., 2012).

Heat stress can have a direct impact through behavioral and metabolic changes in the animals, such as decreased feed intake, increased energy requirement, and decreased conception rates (Das et al., 2016). Indirect impacts are felt through (i) a mismatch between increasing water demand and decreasing water supply; (ii) increased pest and disease pressure as a response to changes in pathogen development, vector distribution, and disease transmission rates, oftentimes in combination with reduced disease resistance; (iii) biodiversity losses, in terms of both loss of habitats, plants, and animals and a diminished gene pool for future adaptation; (iv) changes in quantity, quality, and composition of feed resources; and (v) changes in overall system productivity and livelihood patterns (Ali et al., 2020; Das et al., 2016; Rojas-Downing et al., 2017; Vermeulen et al., 2012).

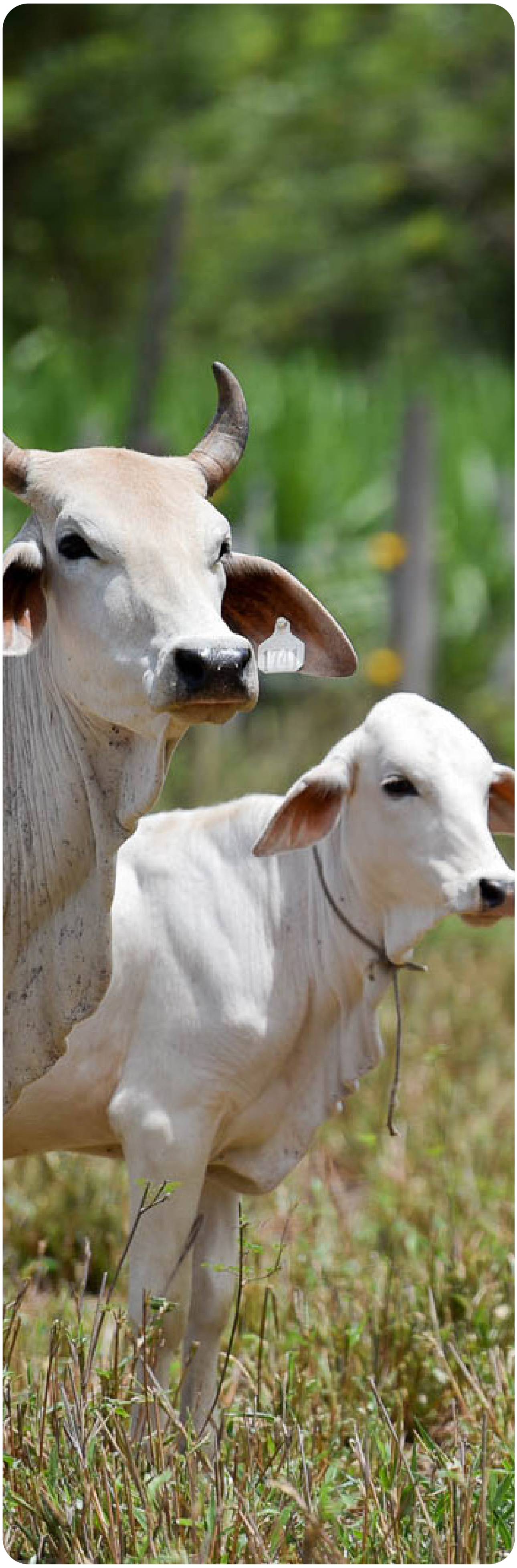
Arguably the most important climate change impacts are those mediated through the climate's impact on what the animals eat, that is, the quality and quantity of feedstuffs and drinking water (Lacetera, 2019). Few global or regional assessments, however, consolidate information on the expected impact of climate change on feed resources. These are indeed complicated as a wide variety of feed baskets exist, consisting of different combinations of crop residues, planted forages, native grasses, grains, and additives. Typically, feedlot-based ruminant and monogastric production depends on a higher share of feed in the form of grains edible by humans or produced on land suitable for human food production, while extensive grazing systems often already show low efficiencies due to low primary production in addition to low nutritional density of the feed. The impacts of climate change on crop residues, legumes, and grasses are varied across feed items, regions, and systems (Vermeulen et al., 2012). They express themselves in terms of changes in overall biomass production and feed availability, changes in feed quality, and changes in species and feed item composition (Vermeulen et al., 2012).

Regions identified as the most vulnerable to climate change, such as sub-Saharan Africa and South Asia (Nilsson et al., 2022), are also regions where farmers and rural communities rely the most on livestock for food, income, and livelihood, and where livestock are expected to contribute increasingly to food security and better nutrition (Herrero et al., 2014). Adaptation will be needed if households are to cope with the multiple (inter-related) stresses of climate change, population growth, urbanization, globalization, etc. This requires not only considerable public and/or private investment but also real change in on-the-ground behavior.

As the effects of climate change are strongly influenced by species/genetic potential, health, and nutritional status, technical entry points for adaptation include genetic improvement, animal health interventions, and improved feed strategies (Sejian et al., 2015). Other adaptation options require changes at the landscape of the system. Examples include diversification of production and income, shifts in species and production systems, land-use planning and sustainable land management, and protection of ecosystem services (Sejian et al., 2015).

2.6 Conclusions

Livestock value chains can cause considerable negative environmental externalities. Pastures that are heavily overstocked result in degradation. The picture, however, is not all negative. Grazing systems that are properly managed, for example, can make an important contribution to maintaining habitats and landscapes. Similarly, the manure from intensive pig production systems has the potential to improve soil fertility (and does so in many regions), whereas, in others, the pressures on land use are so intense as to cause major pollution of both water and air. However, climate change is affecting livestock production and consequently food security. Livestock are negatively affected by climate change, especially in arid and semiarid regions, thus affecting the nutritional content of animal-based products, which are one of the most important suppliers of global protein and calories to human beings. There is thus an urgent need to promote sustainable livestock production. Evaluating and considering potential environmental impacts of interventions are therefore an important step in development planning.



UNIT 3

Evaluation of the environmental impacts derived from livestock production systems

3.1 Interactions among on-farm feed production, animal herd, and environmental impacts

The composition and production of the feed basket and its relation to herd composition should be the core of the analyses as they have a great influence on the final outcomes in terms of (I) the productivity (expressed as energy (kcal), proteins, and micronutrients), (ii) environmental (use of natural resources and assessment of environmental impacts), and (iii) economic evaluation of livestock systems. Figure 1 shows the main inputs that shall be accounted for in calculating environmental impacts and natural resource use from feed basket production.

When performing the environmental and productivity analysis of a livestock system and its attached feed production system, the process starts with a breakdown of the feed basket composition into single feedstuffs. For every feed product included in the feed basket, information about its main characteristics shall be collected from primary or secondary sources. The feed components of the feed basket are produced both on-farm and off-farm. Key contributors to environmental impacts are on-farm activities related to cultivation and harvesting of forages and crops, which include (i) on-farm use of water and land, application of agrochemicals, and use of other inputs; and (ii) off-farm processes regarding production, processing, and transportation of commercial feed, agro-industrial by-products, minerals, crop residues, additives, and grains. The amount of feed used, which is essential for the determination of environmental burdens, shall be based on the calculated intake by the animals over a defined time period, which usually corresponds to one year. This is best estimated indirectly according to animal energy and protein requirements (FAO, 2016b). Considering this, in the environmental assessment of feed basket production, the possible environmental impacts originating on-farm (home-grown feed) from direct production and processing, and outside the farm from the production, processing, and transportation of feedstuffs and inputs used by the farmers, when corresponding, should be evaluated (Figure 1).

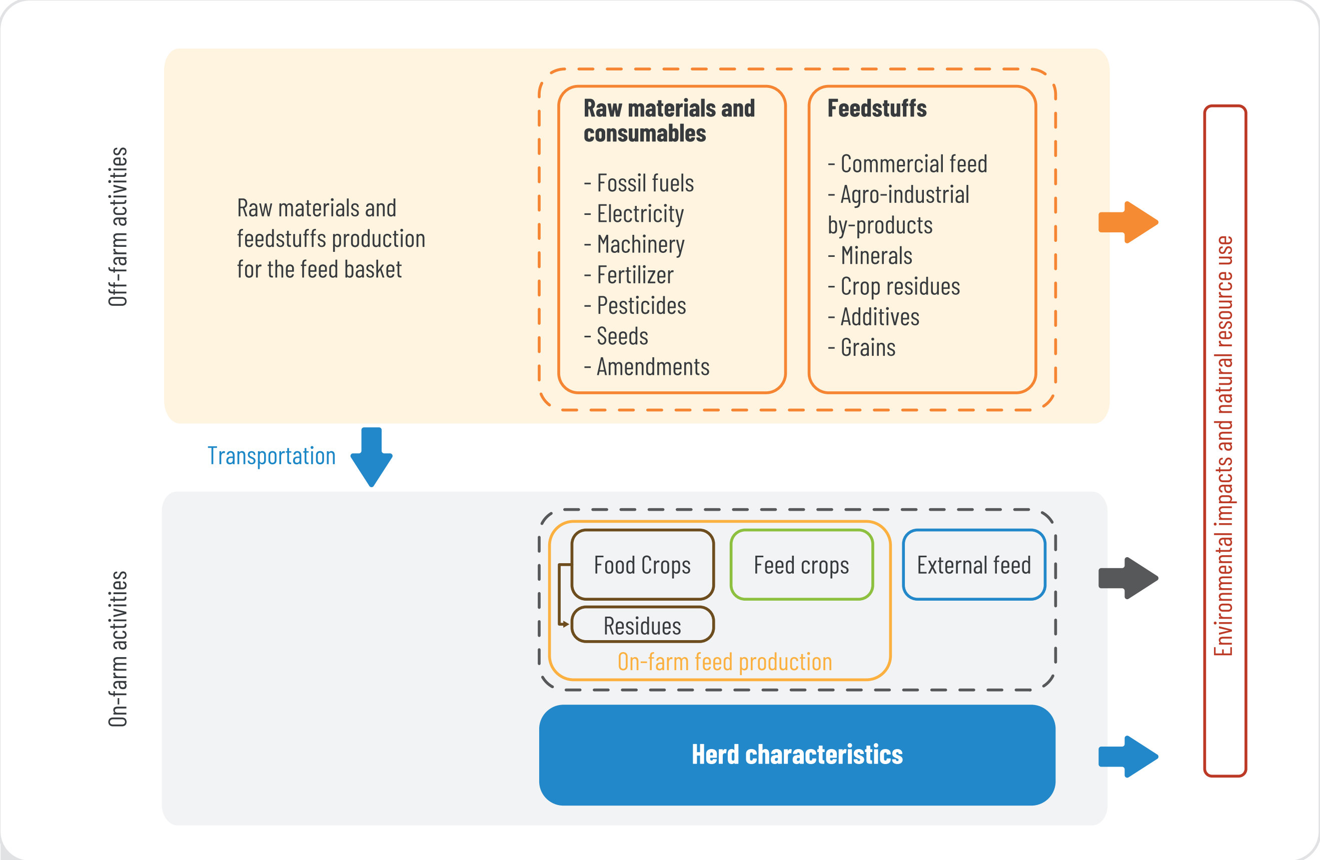


Figure 1. On-farm and off-farm environmental impacts derived from feed basket composition.

To calculate the environmental impacts resulting from feed basket production, the following characteristics are usually considered as minimum requirements:

- Dry matter yield and dry matter content of the feedstuffs.
- Protein content of the feedstuffs.
- Gross energy of the feedstuffs.
- Agrochemical application rates.
- Energy and natural resources (land, water, and nutrients) used during the production and processing of raw materials.
- Energy used for transportation

Using these parameters, detailed nutritional models can be applied to calculate animal requirements, related feed intake, and retention and excretion of nutrients. Then, environmental burdens and natural resources used from the production, processing, and transportation of feedstuffs can be determined by using activity factors for each impact category. Primary data can be obtained for crop production, whereas, for a sectoral analysis, data can be obtained from secondary sources, such as statistics (FAO, 2016b; Mukiri et al., 2019).

The total feed intake, in combination with the quality of that feed, also determines enteric fermentation and associated methane emissions. Enteric fermentation is the largest source of emissions in cattle production. Worldwide, related emissions amount to 1.1 gigatons, representing 46% and 43% of the total emissions in dairy and beef supply chains, respectively. In sub-Saharan Africa, this is followed by methane and N2O emissions from manure storage and processing (Gerber et al., 2013). Following IPCC guidelines (IPCC, 2019), one can calculate the methane emissions associated with enteric fermentation on the basis of dry matter intake (converted to gross energy intake) and feed quality. Finally, emissions from manure management are also a function of animal diet characteristics and gross energy intake.

3.2 Calculating the environmental impacts of livestock production

3.2.1 Overview

Figure 2 shows a full picture of the interactions among feed basket and herd characteristics and the effects of these interactions on the environmental impacts generated by livestock systems. Figure 2 shows that environmental impacts and natural resource use are heavily influenced by herd and feed basket composition, thus emphasizing the importance of animals and feed in the interactions of livestock systems with the environment. Therefore, characteristics from the herd and feed basket composition would flow into the environmental, economic, and productivity modules when evaluating the baseline and intervention scenarios for improving yield and environmental behavior of the livestock value chain from a modeling perspective.

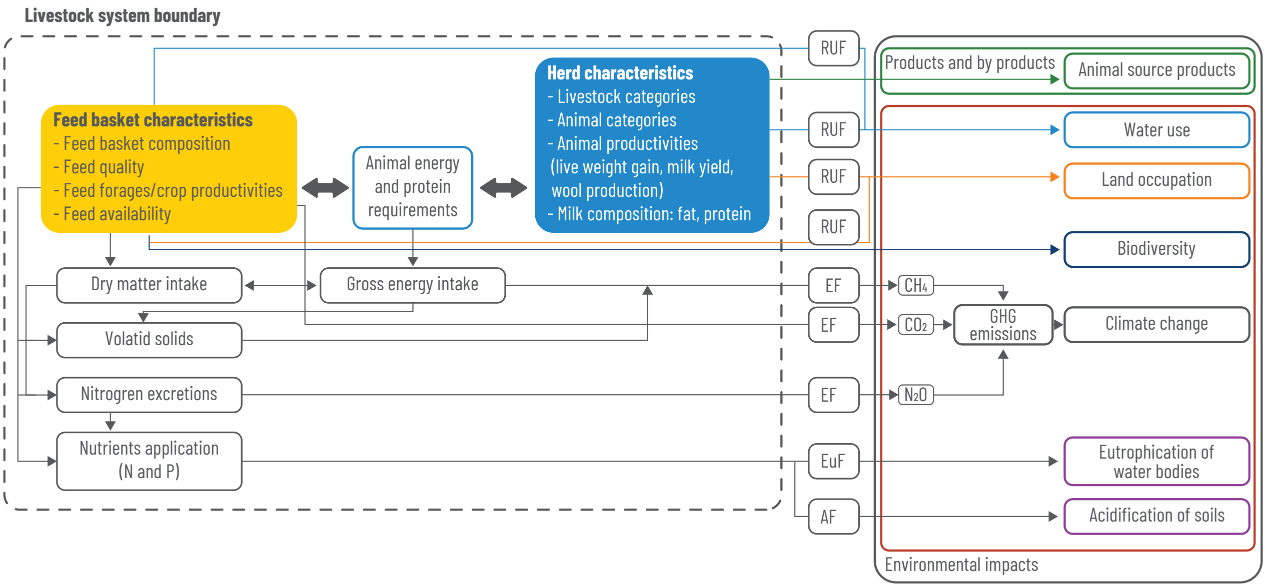


Figure 2. Interactions among on-farm feed production, animal herd, and environmental impacts of livestock production systems.

3.2.2 On-farm feed production

Figure 3 shows the natural resource use and main environmental impacts derived from on-farm forage and crop production for animal feeding. Feed types include (i) crop residues, (ii) grains, (iii) cultivated forages/feed crops, (iv) pastures and rangelands, and (v) supplements.

On-farm feed production processes demand land, water, and nutrients. However, the activities involved in feed production also have a great influence on the availability and quality of natural resources and biodiversity (Figure 3). The use of natural resources is usually measured with the environmental impact categories of land occupation, land-use change, water footprint, and nutrient balance calculations. In addition, the environmental impacts of on-farm processes or activities such as agrochemicals and manure application, burning of fossil fuels, electricity use, and use of consumables are quantified with the following impact categories: climate change (usually measured as the carbon footprint), soil erosion, acidification of soils, eutrophication of water bodies, non-renewable energy use, biodiversity, and nutrient balances. For on-farm feed production processes on small and medium farms, impacts related to transportation are minimal, as in most cases feed is manually carried from the field to the farm; therefore, transportation is usually omitted.

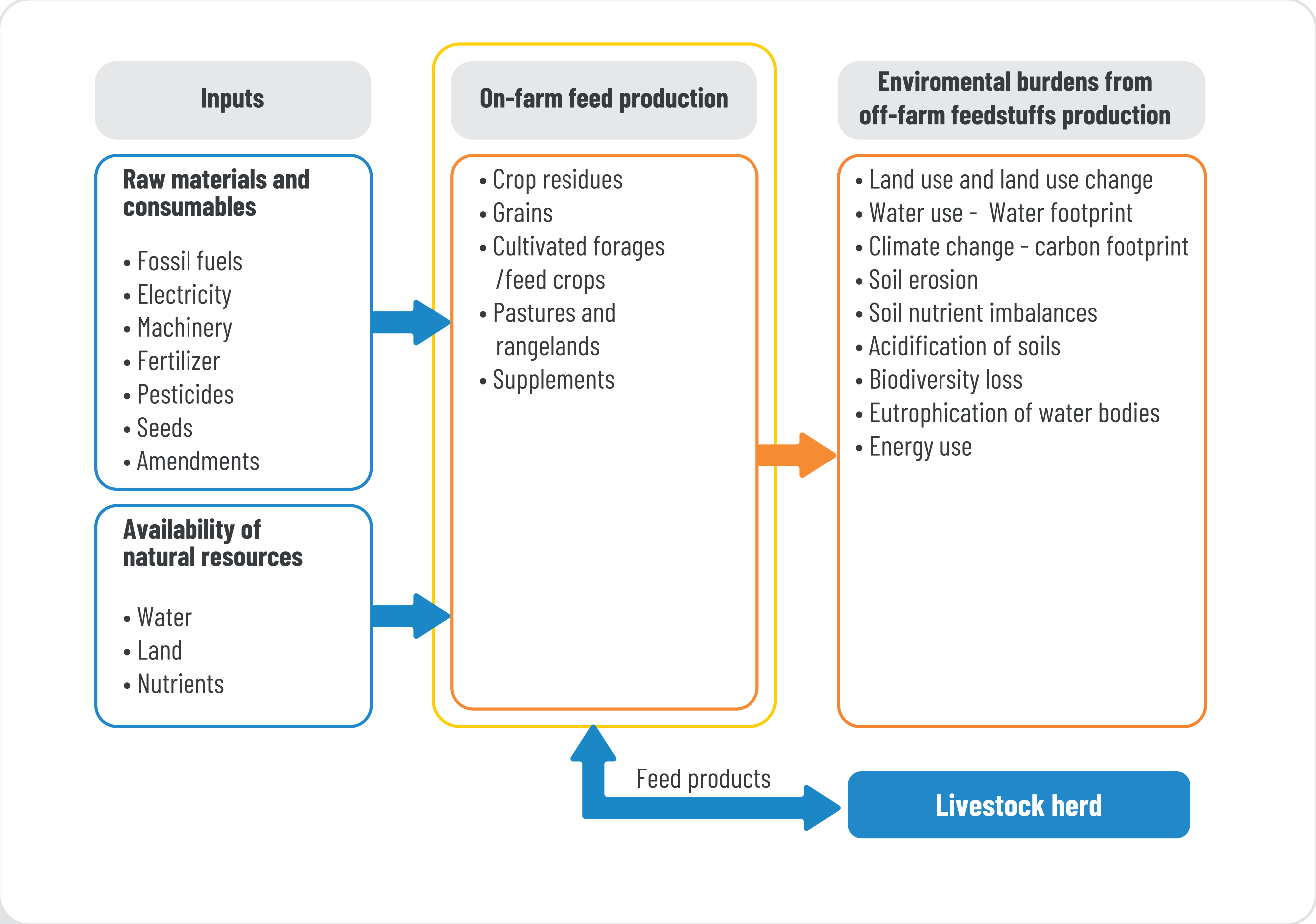


Figure 3. Natural resource use and on-farm environmental impacts derived from crop and pasture production for animal feeding.

3.2.3 Off-farm feed production

The main environmental impacts associated with the manufacturing of external feedstuffs and raw materials for on-farm feed production (upstream processes) are shown in Figure 4. External feedstuffs include commercial feed or concentrates, agro-industrial by-products, minerals, crop residues, additives, and grains. Transportation is an intermediate step between the other stages. Therefore, transportation of raw materials from the manufacturing site to the farm should be considered as it generates considerable environmental burdens. Usually, for off-farm production processes, environmental impacts and natural resource use derived from raw material production are estimated by using environmental impact factors (e.g., the emission factor for estimating GHG emissions) or resource-use factors (e.g., land-use factor for estimating land occupation), in addition to the amount of inputs used by the livestock system in a defined period of time. These factors capture the use of natural resources and/or the environmental impacts of all the activities behind the manufacturing of a product.

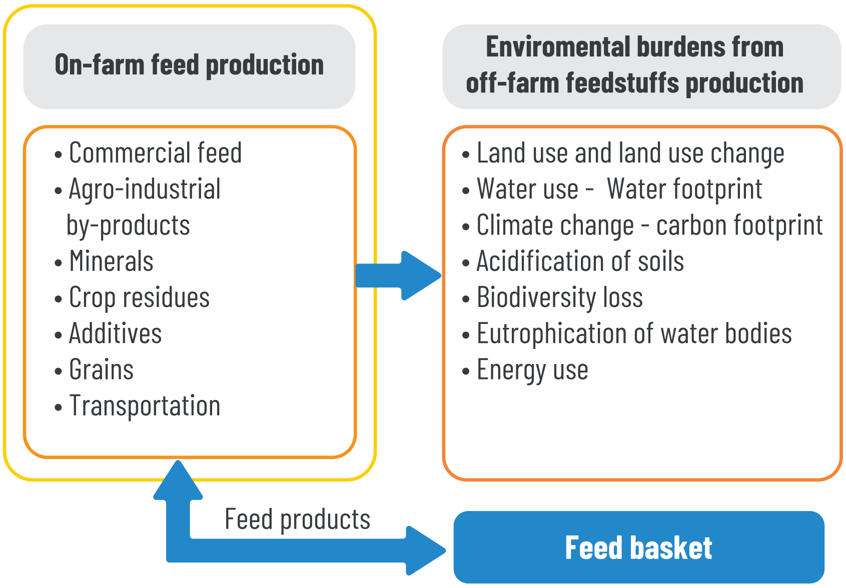


Figure 4. Natural resource use and off-farm environmental impacts derived from feedstuff production for animal feeding.

3.2.4 GHG emissions from the animal herd and feed production

Energy and protein requirements of animals (estimated from herd characteristics) are key to estimating the amount of feed required (gross energy intake; dry matter intake) as well as the environmental impacts that arise from different on-farm activities in agricultural/livestock systems (Figure 2). The estimation of animal energy requirements includes all the energy required by the herd for maintenance, movement, growth, gestation, and milk and liveweight production. For carrying this out, it is necessary to obtain detailed information about the type of livestock, animal categories, number of animals, average liveweights, and productivities of the main outputs of the farms. The strategy to fulfill the animal energy and protein requirements should be established by considering first the availability of local feed, which would determine the feed basket characteristics. In addition, feed quality and quantity influence the productivity and growth of animals, for example, milk yield, liveweight gain, and wool production. Moreover, these two aspects (feed quality and quantity) have paramount importance as they act as limiting factors for animal production, as the lack of feed restricts livestock production.

Animal rations are usually composed of various feed ingredients. The features of each feed item should be considered for calculating the average feed basket composition in terms of digestibility, crude protein content, nitrogen content, dry matter content, fiber content, and dry matter production, given the percentage of inclusion of each in the diet. In livestock systems, the main feed ingredients of the feed basket are usually forages, cereal and legume crops and their crop residues, agro-industrial by-products (by-products from non-feed crops, e.g., oilseeds, cereals, etc.), commercial concentrates (mixtures of different high-quality ingredients), and minerals. However, in developing countries, forages, cereals, legume crops, and crop residues have an essential role in the feed basket of livestock as they are the main components of it, and the use of external feeds is scarce. To establish the availability of feed resources for livestock use in a specific region or agro-ecological zone, the total dry matter, metabolizable energy, and protein production from all the forages and/or crops that can be included in animal diets must be calculated. To carry out these calculations, the cultivated areas, metabolizable energy, and dry matter production per unit area of forages and crops must be considered. The above would help to check whether the production of feed in the agro-ecological zone or region is enough to cover the animal herd energy requirements and identify whether there is a positive or negative feed balance.

In addition to dry matter intake and gross energy intake, the volatile solids content in livestock manure is a key parameter in calculating methane emissions from enteric fermentation and excretions (Figure 2). The volatile solids content of manure equals the fraction of the diet consumed that is not digested and is thus excreted as fecal material; therefore, it is calculated as a function of animal diet characteristics and gross energy intake.

Nitrogen excreted by animals is the key parameter for estimating the direct N2O emissions from animals. The amount of N excreted by each livestock species/category depends on the total annual N intake and total annual N retention of the animal (Gavrilova et al., 2019). Considering this, N excretion can be estimated from the difference between N intake and N retention in data. N intake depends on the annual amount of feed digested by the animal and the protein content of the feed. N retention corresponds to the fraction of N intake that is retained by the animal to produce meat, milk, or wool.

On-farm activities related to feed production (such as soil amendment application, burning of grasslands or croplands, burning of fossil fuels by machinery use, and electricity use) are the main sources of direct CO2 emissions from livestock systems. Therefore, the characterization and quantification of these activities are important in estimating the GHG emissions generated.

3.2.5 Total land occupation

This impact category corresponds to land requirements for all kinds of activities developed in livestock systems as well as those related to the production process of raw materials used by them. The cultivation of feed is the activity that requires more land (see sections 3.2.1 and 3.2.2), followed by the area for keeping the animals. Therefore, land occupation corresponds to the sum of all the land area needed to operate the livestock system, mainly feed production and livestock keeping (Figure 2).

3.2.6 Water use

Globally, substantial water resources are used to produce fodder crops and for grazing. About 37% of the water used is allocated for crop production and 32% of the total evapotranspiration comes from grazing lands and 33% from arable land (Steinfeld et al., 2006). Usually, feed production in livestock systems accounts for most of the water use in the form of evapotranspiration during crop and pasture growth (Rotz et al., 2013; Tichenor et al., 2017). Therefore, when the feed basket is mainly composed of low-productivity crops and natural forages (not improved forages), the efficiency of the whole livestock production system is low and the water resource use is high. In addition, almost all the land use in the whole livestock value chain is allocated to crops and pastures (FAO, 2016a). Therefore, improving crop and pasture yields and better land management, such as converting land to other uses or restoring degraded rangeland areas, as well as technologies to improve feeds (e.g., crop and grass yield enhancements) would help to improve the efficiency of water and land use of the livestock value chain as well as feed crop production.

According to The Water Footprint Network (WFN) (https://waterfootprint.org/), water use is defined as the amount of freshwater used to produce each of the goods and services we use. Water use includes any water withdrawal, water release, or other human activities within the drainage basin impacting water flows and/or quality (FAO, 2016b). Water use in livestock production systems is mainly the water required for feed production, water for animal consumption, and water for carrying out all activities for maintenance of the system (Mekonnen and Hoekstra, 2010). Feed production is considered as the greatest water-consuming activity in livestock systems, which makes this stage of production key in the estimation of the water used (Drastig et al., 2021). Therefore, detailed information from feed production and the animal herd would determine the water use from livestock systems (Figure 2). The water used by livestock systems would be the sum of all the water consumed by the on-farm and off-farm activities involved in the production process.

3.2.7 Freshwater eutrophication potential and acidification potential of soils

The use of agrochemicals (such as fertilizer and pesticide) is limited in non-specialized livestock systems from developing countries, which suggests that nutrient surpluses are not the case. However, depending on the characteristics of livestock systems, a possibility of nutrient runoff and leaching from agrochemical application and excreta management could exist. The above could lead to environmental impacts such as eutrophication of water streams and acidification of soils. Eutrophication refers to an excess of nutrients (mainly nitrogen and phosphorus) in water from fertilizer application to crops and grasslands for feed production, with little contribution of nutrients from animal manure management (European Commission, 2013). This accelerates the growth of algae, which leads to a decline in the oxygen concentration in water bodies. It has been reported that feed production is an extremely important contributor to the eutrophication potential in the life cycle of the livestock supply chain (FAO, 2016a). Therefore, detailed information from feed production would determine the calculation of the eutrophication potential from livestock systems (Figure 2). The eutrophication potential would be the quantification and sum of all the processes that contribute to nutrient application to the environment.

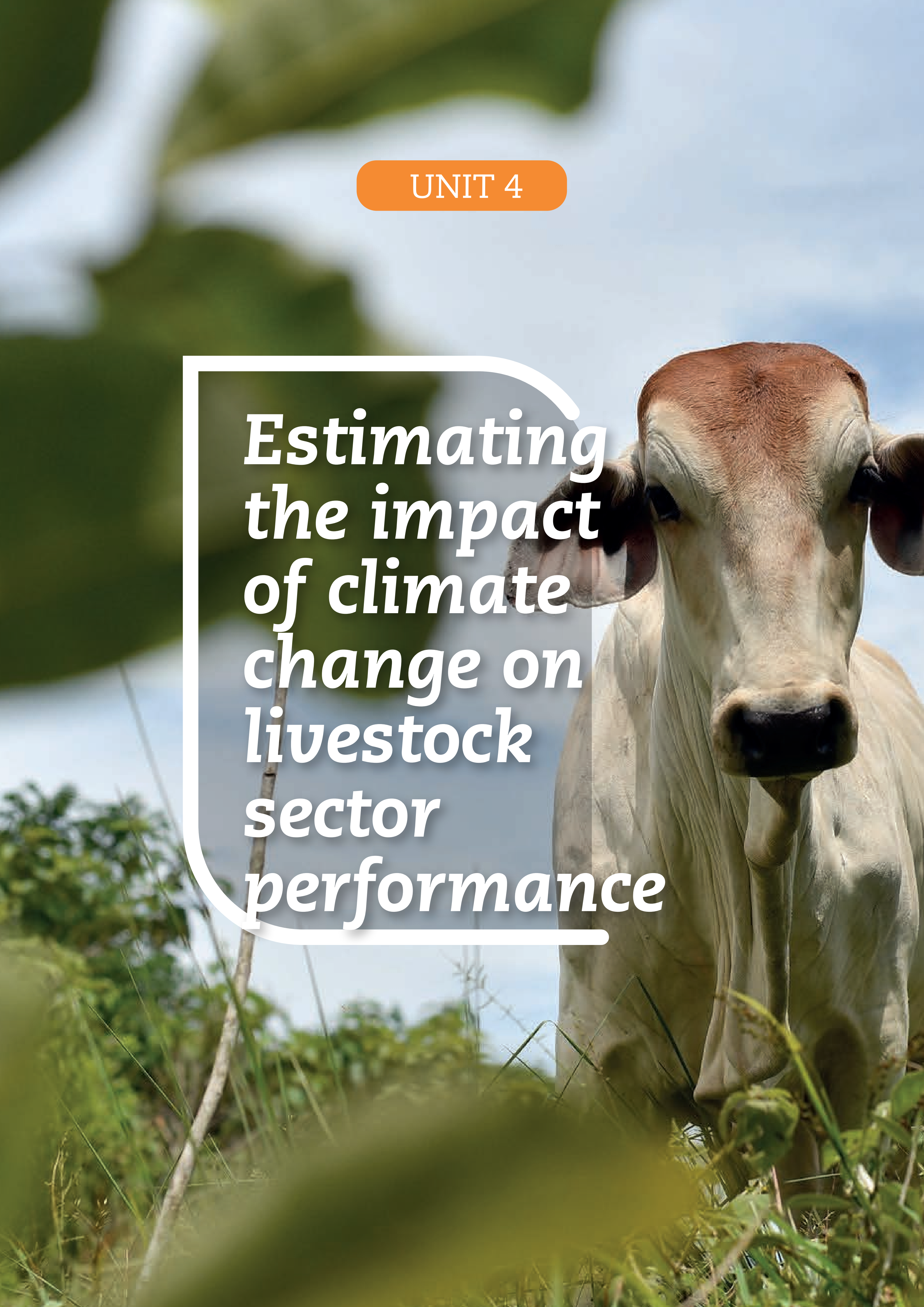
Acidification potential addresses impacts due to acidifying substances in the environment (FAO, 2016b). Nutrients, mainly nitrogen in fertilizers used to produce feed (crops and pastures), and manure management can emit nitrogen oxides (NOX), ammonia (NH3), and sulfur oxides (SOX), which lead to the release of hydrogen ions (H+) when pollutants are mineralized, thus contributing to the acidification of soils (FAO, 2016a). Therefore, detailed information from nitrogen applications from fertilizers for feed production and from excretions would determine the acidification potential of livestock systems (Figure 2). The acidification potential would be the quantification and sum of all the processes that contribute to nutrient NOX, NH3, and SOX emissions to the atmosphere.

3.3 Impact category indicators

Each impact category has a related "impact category indicator," which is a quantifiable representation of it (ISO, 2006). For example, for the GHG emissions generated by livestock systems, characterization factors, known as global warming potentials, specific to each GHG can be used to aggregate all of the emissions to the same impact category indicator, that is, kilograms of CO2e per functional unit. Table 2 displays the most common impact category indicators used for the impact categories mentioned above.

Table 2. The most common impact category indicators for each category of environmental impact considered.

Impact category	Impact category indicator
Climate change	kg CO_2 equivalent
Water use	m^3
Land occupation	m^2
Non-renewable energy use	MJ
Eutrophication	kg PO_4 equivalent
Acidification	kg mol H^+ equivalent



UNIT 4

Estimating the impact of climate change on livestock sector performance

Few quantitative data are available on the impact of climate change (CC) on livestock performance (Escarcha et al., 2018). In the following sections, we provide initial examples and ideas about how modeling can help make such quantitative estimates. As part of the One CGIAR Foresight Initiative, a detailed review of the literature on the impacts of climate change on livestock will be undertaken. We will use this foresight review/report as a basis for refining these ideas and developing equations for quantifying the CC impacts on livestock performance that can be integrated into LMP modeling tools.

4.1 Heat stress

Heat stress has a direct effect on livestock productivity. The most likely impact pathway is through decreased feed intake, nutrient absorption, and feed conversion efficiency, whereas, in extreme cases, livestock mortality will increase and fertility will decline (Escarcha et al., 2018; Thornton et al., 2022).

Using current and projected temperature-humidity index (THI) calculations, Rahimi et al. (2020, 2021) show that the frequency of dangerous heat stress events, which result in significant decreases in productive and reproductive performances, has increased, and they estimate that these will increase further under future climate conditions. Thornton et al. (2022) estimated the comparative static change in the value of cattle milk and meat production from heat stress-induced losses at the global level. Their loss estimates are based on bioenergetic equations that relate changes in dry matter intake (DMI) to both cold and hot, humid weather. Changes in DMI were converted to changes in milk and meat production and valued using early 20th-century world prices (i.e., constant 2005 U.S. dollars).

Logistic regression could be explored for estimating the statistical relationship between weather and mortality data. The impact of the changes in mortality rate in response to changes in weather data or climate scenarios could then, through a dynamic herd model, be translated into changes in herd size and composition.

4.2 Quantity and quality of feed

The impacts of climate change on feed are usually described in terms of quantity and quality (Escarcha et al., 2018; Rojas-Downing et al., 2017; Thornton et al., 2009). It has been reported that increases in temperature and droughts as well as shifts in seasonal patterns (from drier and hotter climates) decrease pasture and forage crop production and cause changes in the temporal pattern of rangeland and crop production (Escarcha et al., 2018). Rangeland and crop/

forage models have been applied to estimate biomass production under different CC scenarios (Senda et al., 2020). Coupling a full-fledged crop and rangeland model with LMP modeling tools might prove too complicated and data-intensive. It might, instead, be worth exploring if relationships exist between weather/climate and availability and quality of feed. This could be done by applying correlation and multivariate statistical analyses at the agro-ecological zone or regional level by considering variables of interest regarding climate, environment, livestock production, farm management practices, and feed characteristics.

4.3 Pest and disease pressure and knock-on effects on herd size and composition

Climate change highly affects livestock diseases. The main direct impact that has been reported corresponds to a reduction in the immune and endocrine system due to heat stress, which makes animals more susceptible to diseases (Thornton et al., 2022). In addition, climate change affects the emergence, spread, and distribution of livestock diseases by pathways such as higher temperatures that affect the expansion of pathogens, shifts in the distribution of diseases and pests that could affect animal populations, and the distribution and intensity or severity of animal diseases and their vectors (Thornton et al., 2019). However, knowledge gaps exist on the impacts of CC on zoonotic and other livestock diseases (Thornton et al., 2019), and there is also a lack of capacity to interpret and use climate models for disease prevention (Escarcha et al., 2018).

Studies on disease and CC face several challenges, which include a mismatch in spatio-temporal resolutions of climate change and disease data, lack of data for analyzing shifts in geographical range of vectors and pathogens, climate change as one of the many drivers of infectious diseases, and lack of capacity to interpret and use climate models for disease risk prediction, among others (Bett et al., 2017). To overcome these challenges, quantitative evaluations regarding the impact of CC on the burden of infectious diseases can be performed by combining data from existing studies with estimates of projected global climate change (Saker et al., 2004). Complex models can be applied to identify the possible effects of CC on the geographic distribution of, and vectorial capacity in, vector-borne diseases (Rees et al., 2021). These kinds of models can either integrate the effects of climate on various components of the transmission cycle or, in a simpler way, perform statistical correlations among the current distribution and characteristics of diseases and climate variables of interest (Bett et al., 2017; Rees et al., 2021; Saker et al., 2004).

4.4 Water availability

Water and land resources are key inputs in livestock production systems. Climate change affects water availability, and water scarcity and depletion are reported to seriously diminish livestock productivity (FAO, 2019b; Naqvi et al., 2015). Water consumption throughout the life cycle of livestock may lead to decreased availability of water in an area and may cause damage to the environment (FAO, 2019b). The severity of water resource deficit depends on the demand for water compared with its replenishment. In addition, the negative impacts of CC on freshwater systems are expected to outweigh the benefits of overall increases in global precipitation due to warming (Thornton et al., 2015). However, substantial knowledge gaps exist on the potential impacts of CC on water availability in livestock systems and its effects on livestock productivity (Thornton et al., 2019). Therefore, water availability and scarcity at the regional or agro-ecological zone level should be assessed under CC scenarios. Remote-sensing images and geospatial information could be explored for determining the interdependency among weather/climatic variables, surface-water and groundwater resource characteristics (e.g., water fluxes), precipitation (historical data and projections), livestock productivity, distances of farms (or communal grazing areas) to surface-water bodies, and other variables of interest. The impacts of the changes in livestock productivity, precipitation, and water body characteristics in response to changes in weather data or climate scenarios could then be translated into changes in annual production rates.

UNIT 5

Operationalizing joint economic-environmental assessments

5.1 Engagement

By providing comprehensive and reliable information, livestock-environment assessments aim to contribute to sustainable livestock sector development. To ensure that the results and insights of the assessments are taken up and contribute to more-informed planning, it is important to integrate them in decision-making processes through early involvement of stakeholders. This raises awareness, creates support for the issue and its solutions, and increases the likelihood of recommendations being implemented. Engagement in the evidence-generating process is often at least as important as the actual information produced.

National governments and other stakeholders have recognized that livestock, and to some extent aquaculture, have significant environmental footprints. Improving the resource-use efficiency of livestock and aquaculture practices would result in rapid environmental gains (Notenbaert et al., 2016). Evidence created through impact assessment at the local farm and landscape levels can be extrapolated and used to design national and regional incentive schemes or regulatory frameworks to ensure appropriate governance mechanisms and significant investment at those levels (Figure 5). The need for a more detailed understanding of the environmental impact of livestock and fish production should be highlighted, and potential gains communicated and integrated into policy frameworks at different levels (Notenbaert et al., 2016).

The establishment of a coalition of change is included in the early stages of the process for developing the LMPs (Rich et al., 202019). The coalition of change has been conceived to support the constitution and the mobilization of a national team, such as a committee of experts representing various disciplines and institutions, and a coalition of partners that oversee realizing the diagnosis of the livestock sector and validation of results, respectively (Bahta et al., 2020). In addition, it determines the modalities of the implementation of the methodology to ensure broad-based participation by stakeholders, reports on initial assessments, and creates a database from stakeholder interactions and other sources. Within the coalition of change, three stages are distinguished: (i) setting up the team, (ii) initial assessments, and (iii) stakeholder interactions. In the first stage, the team must be set up by including institutions and country experts, for example, representatives of ministries of environment and/or agriculture, who will be in charge of the establishment of the budget. In the second stage, constraints and opportunities in the livestock sector are established and include the availability of quality data, review of policy and technical environment, and the roles, representation of the region, and country officers. The third stage involves stakeholder interactions within the sector, between sectors, and among national, county, and regional economic blocks. It will therefore be important to ensure ample representation of environmental experts.

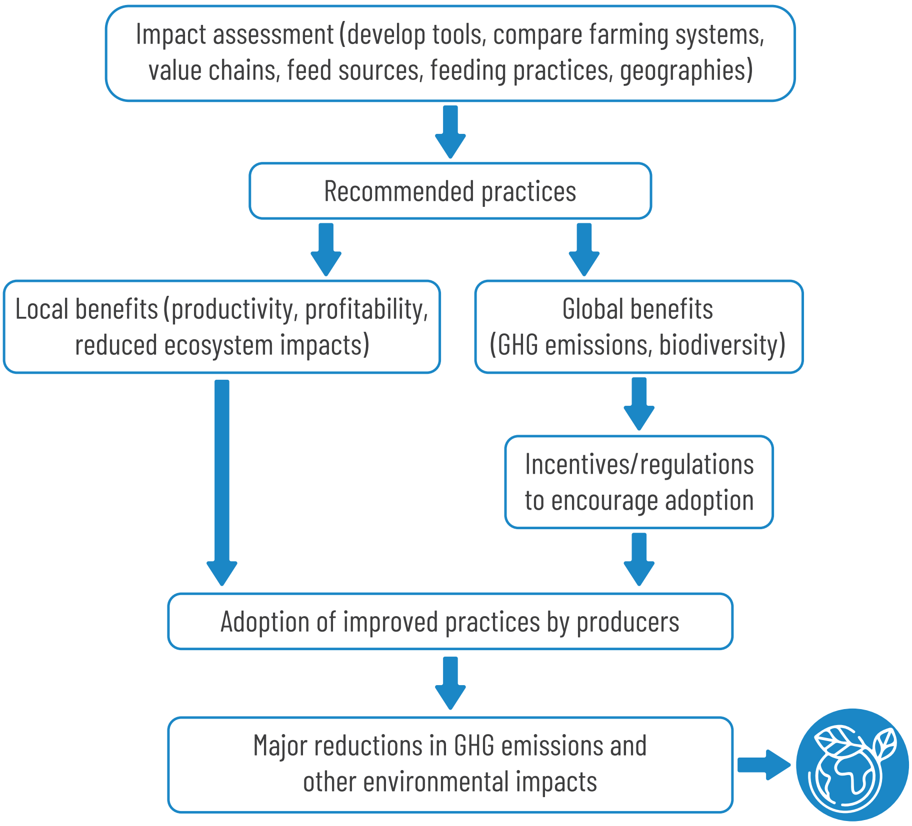


Figure 5. Pathway to impact (adapted from Notenbaert et al., (2016).

5.2 Baselines, interventions, and scenarios

5.2.1 Examples of intervention scenarios

Environmental impact assessment follows a similar step-wise procedure as what is done in terms of the economic modeling in the LMPs. In the first step, the baselines are set. A second step entails the actual ex ante impact assessment so that the potential impacts can be compared against the baselines.

Livestock production systems are highly heterogeneous, diverse, and dynamic. These differences influence both the applicability and the potential impacts of interventions. The first baseline step therefore involves stratifying national livestock production into different systems that are assumed to have similar footprints and respond homogeneously to proposed changes. The quantification and description of the possible environmental impacts derived from external feed and raw material production and from on-farm feed production and animal herd management, considering their current characteristics, give the baseline scenario for each of the systems.

When assessing the potential impacts of interventions, scenarios of alternative intervention strategies need to be constructed and compared in reference to a baseline.

Considering the baseline estimations of the environmental, productivity, and economic performance of livestock systems, alternative intervention scenarios can be modeled on the basis of assumptions, for example, on choosing alternative raw materials, increasing crop yields, enhancing feed quality, and improving livestock management practices, among others. Intervention scenario results would give increases/decreases in productivities of livestock products as well as in the environmental impact categories evaluated when compared to a baseline.

5.2.2 Examples of intervention scenarios

5.2.2.1 Establishment of intervention scenarios to cover feed imbalances

This impact category corresponds to land requirements for all kinds of activities developed in livestock systems as well as those related to the production process of raw materials used by them. The cultivation of feed is the activity that requires more land (see sections 3.2.1 and 3.2.2), followed by the area for keeping the animals. Therefore, land occupation corresponds to the sum of all the land area needed to operate the livestock system, mainly feed production and livestock keeping (Figure 2).

Initially, a baseline scenario should be developed. In this scenario, a feed balance should be carried out for a livestock category in a specific agro-ecological zone. This must be done by considering current forage and crop production and animal herd energy/protein requirements according to the actual animal inventory. According to the feed balance outcome, different intervention scenarios must be established to cover possible feed imbalances when the feed production of the territory is not enough to cover livestock requirements.

Increasing forage and crop yields

Considering the feed balance, if current feed production is not enough to cover livestock requirements, an increase in production rates is needed. To accomplish this, it would be necessary to determine whether a range exists for improving the productivity of forages and crops and/or whether expanding the current cropland area to produce more feed is possible. The improvement of crop and pasture yields could lead to fulfilling animal requirements without expanding current livestock areas. For instance, potential increases in productivity can be identified by performing a "yield gap analysis," which is used to estimate the extent to which agricultural production can be increased for a particular agro-ecological zone and to identify the factors that constrain production. This analysis defines the differences between actual and attainable yields, where attainable yields are the maximum productivity achievable given locally available resources and technologies.

However, if by increasing the productivity of feed biomass production there is still an imbalance between the offer of feed and what animals require, this could be covered in two ways: by expanding forage production areas or by sourcing feed biomass externally.

Expansion of forage land areas

It is important to identify whether a window exists for expanding feed crops and animal grazing areas that allows an increase in feed production and thus fulfilling animal energy requirements with feed locally produced. This must be done considering the remaining land for livestock activities in a specific region to avoid expansion at the expense of forests and crops for human consumption. The expansion of land areas for forage feed production could have several negative impacts on biodiversity, land-use change, and GHG emissions, among others. Therefore, this should be considered only if land is still available for livestock production within a specific region or agro-ecological zone. Therefore, if it is not possible to expand forage areas without any direct land-use change impact on food crop production and forest, and the feed imbalance remains, the inclusion of higher percentages of crop residues and external feed in diets should be evaluated to cover animal energy requirements.

Increments of crop residues in the animal feed basket

The inclusion of crop residues in livestock feeding is a common practice among smallholder livestock farmers (Castellanos-Navarrete et al., 2014). Therefore, including this feedstuff in animal feed basket composition would be another option for fulfilling livestock energy requirements. However, the quality of crop residues is often low. In addition, as the retention of crop residues in the field helps to conserve a considerable amount of nutrients on-farm, their use for animal feeding would lead to poor nutrient-cycling efficiencies at the farm scale. Therefore, policymakers should be careful when considering this type of measure.

Inclusion of external feed and concentrates in the diet

To fulfill animal energy requirements, the inclusion of high-energy and -protein feedstuffs would be a great option. However, as external supplementary feeding represents a high economic expense, farmers' purchasing power and access to markets should also be considered when interventions for covering feed imbalances are established. Additionally, the manufacturing process of these feedstuffs usually generates off-farm environmental impacts, which must be charged to livestock production systems.

5.2.2.2 *Improved productivity through breeding and animal health interventions*

Considering the existing yield gaps in livestock systems in developing countries, animal productivity increases are feasible with changes in management, breeds, feed, and health practices (Baltenweck et al., 2021; González-Quintero et al., 2022). One of the key constraints farmers face is access to animal health inputs and services as well as breeding advisory services (Baltenweck et al., 2021). To tackle the above, some technology interventions such as improved animal breeding and better health practices have been proposed to increase animal productivity in developing countries (Baltenweck et al., 2021). Depending upon the biophysical, agro-ecological, and market conditions that livestock systems face in a specific region or agro-ecological zone, interventions need to be proposed and could include artificial insemination, genetic selection, adoption of new livestock breeds and genotypes, critical vaccinations and parasite control programs, and technical assistance (Marshall et al., 2019; Shapiro et al., 2015). Various combinations of these technology interventions could generate higher animal productivity and income for the farmers, as was proposed in the LMPs (Shapiro et al., 2015).

5.2.2.2 *Internalizing the carbon cost into the price of livestock products*

Environmental costs from negative externalities such as GHG emissions are not considered in the cost structure of livestock products or the whole livestock value chain and are thus a burden on other market participants, future generations, and the natural environment (Dragicevic, 2021; Pieper et al., 2020). These negative externalities are typically assessed by means of environmental standards (Dragicevic, 2021). These external costs are not yet included in the market prices for livestock products, thus leading to significant market price distortions (Pieper et al., 2020). GHG emissions from agriculture must be quantified and monetized to close the gap between current market prices and the true costs of livestock products (Pieper et al., 2020). Therefore, to minimize the harmful costs caused by livestock production, externality costs should be charged to the producer prices of livestock (Pieper et al., 2020; Tobey and Smets, 1996).

A broad association between the quantification and monetization of GHG emissions in livestock systems is lacking in the currently available literature for developing countries. Therefore, differentiation in prices between current producer prices and true costs, which includes environmental externalities, must be carried out. To do this, it would be necessary to explore methods for a differentiated quantification and monetization of GHG emissions from livestock systems. One is the LCA methodology, which is a holistic tool to evaluate environmental and social impacts during the entire life cycle of a product (de Vries and de Boer, 2010), in which monetization of impacts can also be included. Monetization of the carbon footprint would allow identifying whether livestock products are highly associated with high external costs (Pieper et al., 2020). In addition, and considering economic theories, if the resulting costs can be addressed by economic policies, they would allow livestock externalities to be internalized according to the polluter-pays principle and at the same time strengthen sustainable consuming behavior (Pieper et al., 2020).

5.3 Feedback loops

Two-way livestock-environment interaction and linkages among the environmental, productivity, and economic performance of the livestock sector necessitate the inclusion of feedback loops, both positive and negative, for example, the following:

- **Positive:** increased productivity ➔ increased manure ➔ increased feed quality and quantity ➔ increased productivity
- **Negative:** increased production ➔ increased GHG emissions ➔ increased climate change and variability ➔ reduced production
- **Negative:** climate change and variability ➔ reduced feed quantity and quality ➔ increased production cost ➔ increased price for livestock commodities ➔ reduced livestock production ➔ reduced climate change and variability

6. Final remarks

This document was developed to give insights into what would be the key component for linking the productivity, economic, and environmental modules of livestock sector models. Improving yields and farmer income are often seen as priorities and development actions are thus designed with these specific aims in mind. However, many proposed farming practices might damage the environment and generate several environmental impacts. Increasing livestock production without improving system efficiency and animal productivity is usually done by increasing animal numbers, which leads to higher consumption of feed and natural resources and to an increase in environmental burdens. Most of the environmental impacts and natural resource use in the livestock value chain occur during feed production. In addition, the feed basket plays an important role in animal performance, given that it must fulfill animal energy and protein requirements. With projections of animal inventories at the regional or national level, we can identify whether the natural resources and locally available feedstuffs are enough to fulfill the projected animal energy requirements, and with this we can calculate the feed balance. The identification of feed imbalances helps to screen sets of interventions focused on feed basket production that would lead to closing the imbalances and improving animal production and efficiency, and thereby farmer income, and to diminish the natural resource use and environmental burdens from the livestock sector. Intervention scenarios such as the increasing productivity of forages and crops, expansion of forage areas, higher percentages of crop residues in feed basket composition, and the inclusion of external feed in the diet should be assessed in a productive, economic, and environmental way, and a starting point for evaluating these three aspects is herd characteristics and feed basket composition.

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