Matière
à débattre & décider

Livestock grazing systems and sustainable development in the Mediterranean and Tropical areas

Recent knowledge on their strenghts and weaknesses

Alexandre Ickowicz and Charles-Henri Moulin, editors

éditions Quæ

3. The quest for efficiency, an approach to increase the contribution of livestock farming to the sustainable development of territories

Jonathan Vayssières, Fabien Stark, Vincent Blanfort, René Poccard-Chapuis, Mathieu Vigne

Introduction: efficiency, from a simple ratio to an operational analysis framework to support the sustainable development of livestock systems

The concept of efficiency has often been used as a relevant analytical framework for reflecting on the evolution of the livestock sector and supporting its transitions. However, the multi-faceted nature of this concept has led to some confusion. But a historical analysis of its use in the evaluation of livestock systems shows that the semantic evolution observed is above all the consequence of an epistemological evolution, i.e., of the knowledge on which the concept is based, and an ideological evolution, i.e., of the values carried by the concept. These developments have resulted in multiple definitions in response to the complexity of the issues with which the sector has been and still is confronted.

Producing more: technical and economic efficiency to meet the challenges of the green revolution

In the production-oriented vision of the green revolution, efficiency indicators were first mobilised to maximize the use of agricultural resources so as to produce the maximum yield and therefore income per structural unit (e.g. kilograms of wheat per hectare or litres of milk per cow). The technical and economic efficiency of livestock systems was the focus of the evaluation of their performance. This was expressed as a ratio between the products and the means of production used, similar to productivity or yield.

Technical and economic efficiency = Product(s) / Means of production used

Among the indicators widely used, we can mention, for example, the quintals of wheat per hectare for crop production or the litres of milk per cow per production cycle for animal production.

Producing better: efficiency for a more thrifty management of energy resources

For some forty years now, however, the notion of efficiency seems to have found a semantic stability with a definition of its own. Efficiency is therefore widely considered to be the search for a better use of one or more natural resources implemented to obtain one or more results. It is expressed as the ratio between the result(s) obtained (products or services) and the natural resource(s) used.

Efficiency = Result(s) obtained / Natural resource(s) implemented

This shift in vocabulary makes it possible to conceive of forms of efficiency other than purely technical and economic efficiency, such as environmental efficiency, and hence move away from a purely productivity-based logic. Efficiency redefined in this way is also distinct from efficacy, which is the relationship between the results obtained and the objectives set, irrespective of the means used to achieve these results.

Efficacy = Result(s) obtained / Objective(s) set

However, this interest in natural resources, in comparison with the previously mentioned technical-economic efficiency, was not initially motivated by the perception of the finiteness of this type of resource due to an excessively high rate of operation, but rather by the increase in their cost. The increase in oil prices during the oil crises of 1973 and 1979 prompted the agricultural sector to reduce its direct and indirect fossil energy consumption, mainly for economic reasons. As a result, the efficiency indicators in agriculture were developed through the assessment of the fossil energy efficiency in agricultural systems, which complemented the measures of technical and economic performance mentioned above. This is most often expressed in megajoules of heat energy contained in agricultural products out of the megajoules of fossil energy consumed directly and indirectly by the production system.

Sustainable production: efficiency and environmental awareness

In the 1980s, there were relatively few analyses of fossil fuel efficiency, due to a significant decrease in the price of fossil fuel linked to a growing supply from other producing countries than those of the Gulf. But these are again experiencing a boom in the early 1990s (Vigne *et al.*, 2012). Dependence on fossil fuel resources is no longer analysed solely in terms of its impact on the economic performance of systems, but by considering the pressing issue of global warming, highlighted by the 1987 Brundtland Report and the 1992 Rio Conference. It is now the major link between fossil fuel consumption and the global warming impact of carbon dioxide (CO_2) that is driving this renewed attention.

In addition, shifting environmental issues has broadened the range of resources included in the efficiency report. While it continues to be studied (Vigne *et al.*, 2012), fossil energy is complemented by the consideration of other resources such as water, nitrogen, phosphorus or arable land. The capacity of livestock systems to use all or part of these resources in a moderate manner is in line with a more global search for environmental efficiency.

In addition, the main issue relating to greenhouse gas (GHG) emissions is leading to a new evolution in the concept of environmental efficiency. The livestock sector is especially well suited to this issue given its significant contribution to this phenomenon through its GHG emissions (Steinfeld *et al.*, 2006; Gerber *et al.*, 2013). It is no longer a question of simply reducing resource consumption per product unit, but rather considering the ratio between two types of product from the activity: undesirable products, often flows that cause environmental pollution (e.g. nitrogen losses or greenhouse gas emissions) and the desirable products.

Environmental Inefficiency = Unwanted Product(s) / Target Product(s)

So it is the environmental inefficiency of livestock activities that is assessed and which reflects its environmental impacts. These impacts are therefore reduced when the ratio, expressed for example in kilograms of CO_2 equivalent per litre of milk or gram of meat, decreases.

But how these indicators are currently mobilised in research and development works to address the contribution of livestock systems to the major environmental issues? The sub-chapter Efficiency to account for the complexity of the contributions of livestock grazing systems to climate change illustrates the relevance of these indicators to two issues where the notion of efficiency is intuitively relevant, namely the careful management of energy resources and the reduction of the livestock contribution to climate change.

Efficiency for a systemic analysis of livestock transitions

The ambiguity of the concept of efficiency as well as the diversity of indicators highlighted above could appear to be an obstacle to the mobilisation of the concept of efficiency for action. The aim is not to assess for the sake of assessing, but to assess in order to improve support for change. In addition, there are issues related to the assessment scales. Improving the efficiency of processes at the animal or plot level will not necessarily maximize the benefits at the farm or territorial level. Observations made at one level of organisation are not necessarily observed at higher levels of organisation. As a result, territorial analyses cannot be based on a mere aggregation of “performances” at farm level. Moreover, considering the organisational levels of sectors and territories requires considering a diversity of processes and stakeholders that go beyond livestock systems alone.

All of these considerations raise an operational question: how can efficiency indicators and evaluation methods be mobilised to support livestock system transitions at different organisational levels? To shed light on this question, the sub-chapter entitled The pursuit of efficiency to support the agroecological transition in livestock systems presents research studies that have used the concept of efficiency to support the transition of livestock systems to more sustainable agroecological systems.

Recognising the multiple services provided by livestock farming

Despite the diverse dimensions that they take into consideration (range of resources mobilised, range of targeted products and range of unwanted products), can efficiency indicators also be mobilised in multi-criteria approaches, in particular with the aim of responding to all of the sustainable development issues that the livestock sector is facing? If livestock systems are to be efficient from a technical, economic and environmental point of view, efficiency indicators must also include social dimensions that have become increasingly significant.

Moreover, in the studies conducted, the products considered in the efficiency indicators are often limited to products for human consumption (milk and meat). However, the multifunctionality of animal and plant production calls into question the quantification of products and services rendered by livestock production. The productive purpose of livestock production is being reconsidered. It is no longer just a matter of ensuring food safety for human populations but also of considering its multiple services, whether socio-economic or ecosystemic (Millennium Ecosystem Assessment, 2005; Dumont *et al.*, 2019).

In the South, for example, while livestock systems are less productive than in the North per animal and per hectare in terms of products for human consumption, they provide a set of important technical and socio-economic services, including the constitution of easily mobilised economic capital, social positioning, the maintenance of a social and economic network in rural areas, and the production of organic manure or animal traction (Alary et al., 2011). Other examples are the ecosystem services provided by livestock, such as fertility transfers and carbon sequestration in soils (Blanfort *et al.,* 2011) or the contribution of grazing to the balance and sustainability of dryland ecosystems are other emblematic examples. Depending on the management methods and ecosystems, grazing can open up landscapes and limit scrub, stimulate plant growth, fertilize soils, accelerate the recycling of nutrients, participate in the spread of seeds, and improve the infiltration of rainwater in vast territories where it is the main economic activity.

Considering the efficiency indicators already established, but also those to be established, the sub-chapter Multicriteria evaluation of efficiency to account for the multifunctionality of livestock grazing systems provides a review of the contribution of the concept of efficiency to better take into account the contribution of the livestock sector to the SDG. This chapter provides an analysis of how these global objectives defined by the United Nations can integrate the multifunctionality of livestock systems, but also the multiplicity of local and global issues, notably through the use of multi-criteria evaluation approaches and the construction of compromises that stakeholders must make.

Efficiency to account for the complexity of the contributions of livestock grazing systems to climate change

Vincent Blanfort, Habibou Assouma, Bérénice Bois, Louis-Axel Édouard-Rambaut, Jonathan Vayssières, Mathieu Vigne

For several decades, the “livestock/environment” debate has fuelled questions about the development of agriculture in the face of global change. This societal debate has largely focused on the negative impacts of livestock farming (Steinfeld *et al.*, 2006) and in particular its contribution to climate change. The livestock sector is responsible for 14.5% of anthropogenic GHG emissions (total for agriculture: 23%). They are mainly due to ruminants, with 65% attributed to dairy and beef bovines and 6.5% to small ruminants. However, ruminants grazing systems would “only” be responsible for 20% of total emissions from livestock (Gerber *et al.*, 2013).

Moreover, the Intergovernmental Panel on Climate Change (IPCC) special report of 2019 “on climate change and land” presents scenarios of evolution that are much more worrying than the previous ones on the impacts of climate change and the necessary adaptation, in particular with regard to desertification, degradation and sustainable land management as well as food safety. However, Livestock grazing systems is also one of the possible levers for reducing emissions. These elements demonstrate that measuring the weight of livestock grazing in global changes is a complex task. This complexity requires us to implement adapted evaluation methods to correctly establish GHG balances (carbon dioxide - CO_2 -, methane - CH_4 - and nitrous oxide - N_2O). These assessments are essential for the operational design, for each situation, of two main types of mitigation actions: (i) to reduce the level of GHG emissions and (ii) to promote the transfer and storage of carbon (C) from the atmosphere to terrestrial compartments in stabilized form.

In this section, we provide a practical illustration of this methodological process, with research programmes implemented in various tropical regions, where very different livestock grazing systems are used. We recommend indicators based on the efficiency concept to better reflect the specific contributions of these systems to global issues, notably those related to climate. These indicators improve the often stereotypical view of the impacts of the livestock sector in general, and of livestock grazing systems in particular (Blanfort *et al.*, 2015b). However, it is not a question of denying these proven impacts, but of specifying their limits and conditions, through integrated methods targeting the processes and their consequences. These methods combine in an integrated manner (i) metrics adapted to the context, (ii) consideration of the levels of organisation and their interrelationship (animal, herd, plot, territory) as well as (iii) the characteristics of the stakeholders involved at each level (farmers, technical support, territory manager).

Are enteric methane emissions at the animal and herd level higher in livestock grazing systems in the South?

Even if ruminants are endowed with this capacity to convert cellulose into quality proteins, the processes of biochemical degradation and forage digestion produce residue. This includes the production of methane gas (CH_4), a consequence of the degradation of membrane walls composed of cellulose, hemicellulose and lignin in the rumen.

Livestock grazing systems (LGS) in tropical and Mediterranean areas are particularly challenged in the debate on methane emissions from cattle: the animal production/methane emission ratio is highly unfavourable compared to more intensive livestock systems in industrialised countries. According to the FAO (Gerber *et al.*, 2013), the global mean GHG emission from bovine animals is 46.2 kg CO_2-eq/kg carcass[12] for meat and 2.8 kg CO_2-eq/kg for milk. These figures are different if we only consider sub-Saharan Africa, Latin America and South Asia: 70 kg CO_2 eq are emitted for the production of one kilogramme of carcass and from 2 to 12 kg CO_2 eq for one kg of milk depending on the productivity of the cows (which is highly variable). These figures are primarily related to enteric methane emissions. Based on ratios per animal or per kilogram of product, they mainly reflect the lower digestibility of feed and the lower productivity of animals in most livestock systems in developing countries, in particular in warm regions. The stakes for mitigation are all the more obvious.

In the North, and in particular in mainland France, the research and support institutions for livestock farming have largely adopted these figures. The mitigation potential could reach 30% of current emission levels. But in the South, the possible alternatives are much less documented. The difficulties in implementing livestock farming techniques that would reduce enteric methane emissions have led many experts to conclude that only reducing the number of animals and setting up intensive farms are effective in reducing sectoral emissions (Thorpe, 2009 in Blanfort *et al.*, 2011).

From a methodological point of view, precautions are required when interpreting these figures, which are the result of a simple transfer of methods designed in the North to the real situation in the South. In addition to the multiple functions of raising livestock

12. The "kg CO_2-equivalent" (CO_2 eq) is a unit created by the IPCC to compare the impacts of the various GHGs on global warming and to be able to aggregate their emissions.

that go beyond the production of meat and milk, the agroecosystems and management methods are also very different. However, the techniques available to estimate the quantities of enteric methane from ruminants on tropical rangelands are limited (Rosenstock *et al.,* 2016), and are not adapted to certain contexts. This is the case for livestok grazing systems in West Africa, where in-vivo rangeland measurements are proving difficult. In regions with a semi-arid climate, the quantities of methane produced per animal depend mainly on the quantity and quality of forage ingested, which fluctuates widely depending on the season.

To assess the magnitude of these variations and identify the appropriate adjustments, in the absence of available in vivo measurements on grazing ruminants, in vitro fermentation experiments of their diet can be conducted. These experiments conducted "in defined and controlled conditions", do not accurately reflect daily enteric methane emissions, because they involve the artificial reconstitution of the rumen. However, in the absence of other adaptive techniques in the Sahelian grazing areas, this method has been used to study the effects of vegetation dynamics on enteric methane produced by bovines in northern Senegal (Doreau *et al.,* 2016). In this region, transhumant farmers are entirely dependent on natural forage, the quantity and quality of which decreases during the dry season. In the rainy season, the diet consists of young grasses that are more digestible and richer in protein than dried grasses and woody plants (trees and shrubs) in the dry season. The study suggests that the ingestion of dry season forages leads to increased methane formation in-vitro. However, since ingested amounts decrease by more than half during this period (Assouma, 2016), daily methane production per animal is not necessarily higher. A study comparing the quantitative and qualitative effects of seasonal changes in feed would be required to complete these initial elements. This is especially true since, while lower feed intake does indeed reduce daily methane emissions (g CH_4/animal/day), it also increases methane yield (g CH_4/kg DM ingested) (Goopy *et al.*, 2020).

Accordingly, in regions with persistent and seasonal forage deficits, the development of forage supplies and low-conversion forage and feed supply chains could offset the increase in methane yields due to the food deficit. Care should be taken to ensure that these changes in practices are not associated with indirect increases in GHG emissions (transportation, land use, etc.). The selection of lower-emitting plants may also be an option for mitigation. Specifically, legumes and ligneous plants contain varying degrees of secondary compounds (tannins, saponins), which are reputed to inhibit methane production by modifying the activity of rumen microbes (Archimède *et al.*, 2018). In the Sahel, bovines naturally consume a significant amount of ligneous material with these properties (Assouma, 2016). However, it would be necessary to determine the effects of these practices on methane emissions (Figure 3.1).

These observations from the field reveal that ruminant diets and their effects on methane production are complex and variable, primarily in view of the diversity of feeds throughout the annual forage season. The various elements can therefore have

Figure 3.1. Faeces bag on young zebu cattle to measure excretion and predict ingestion, in northern Senegal (Assouma, 2016).

antagonistic or, on the contrary, synergistic effects. However, while forages consumed with a low conversion factor (percentage of ingested energy converted into methane) are levers that can be used to reduce emissions, reasoning solely on the basis of methane yield or feed conversion factor is restrictive. This is because GHG emission mitigation must not be obtained at the expense of the performance and well-being of the animal or the environment. Moreover, the parameters relating to methane emissions (emission factor, methane yield, conversion factor) of tropical forages are still insufficiently described, justifying the implementation of studies on local forage resources that take these multiple factors into account.

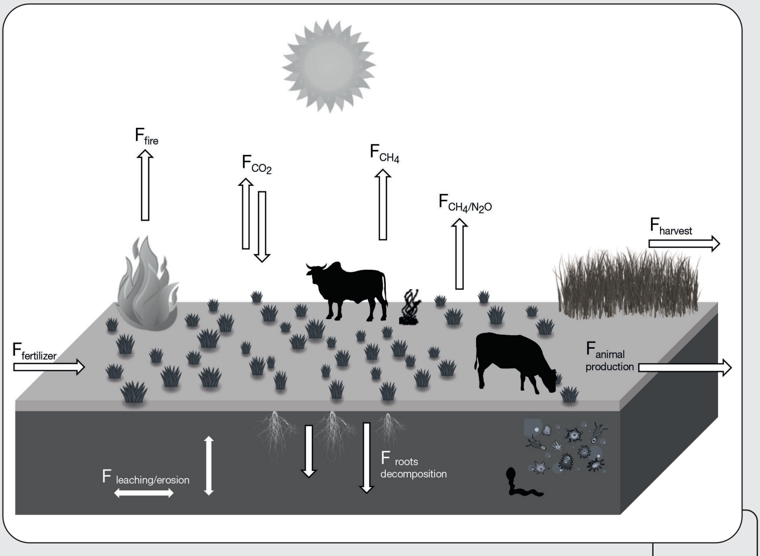
Increasing carbon storage in grasslands and rangelands

Livestock grazing systems have a specific potential to offset some of their emissions through carbon (C) sequestration in the soil and vegetation of grasslands and rangelands. Forage plants capture carbon from the atmosphere by photosynthesis, and accumulate it in the soil through root decomposition (Box 3.1).

These grazing land occupy 30% of the land surface (or 70% of the world's agricultural land), they contain 30% of the world's soil carbon stock. However, this sequestration potential proves to be highly variable (from 0 to 4 tC/ha/yr) depending on the ecological zone, soil characteristics, climatic conditions and agricultural practices (Soussana *et al.*, 2010). As a result, soil management appears to be a key point in controlling these carbon fluxes in the climate change fight. According to Gerber *et al.* (2013), it represents the greatest potential for emission reductions within the agricultural sector.

Box 3.1. Carbon cycle dynamics in grazed ecosystems.

Figure 3.2. Diagram of carbon cycle dynamics in grazed ecosystems (from Soussana *et al.*, 2010).



F = Flux.

In the case of livestock grazing systems, based on grazing or harvesting grasslands, or rangeland, the processes involved in exchanges with the atmosphere are complex and intertwined. CO2 net emissions are derived more precisely:

- for the inputs: from photosynthesis and root decomposition in the form of organic matter, fertilization and animal manure;

- for the outputs: from the respiration of above-ground parts of plants and of the soil-root complex and from the respiration of animals (Figure 3.2).

The balance of these inputs and outputs can lead to carbon storage/removal. As such, grasslands are potential carbon sinks. A distinction is made between carbon storage, which constitutes a net balance of carbon accumulation in the ecosystem (taking into account emissions), and the sequestration process, which only involves carbon inputs.

Given these uncertainties, the scientific references available in the tropical areas on these issues are insufficient. The standard metrics and methodologies used may be inappropriate for a correct assessment of grazing ecosystems in these regions, where the overall storage potential is high in relation to the areas concerned. The research presented in this section contributes to establishing references on carbon sequestration processes at the plot scale in two tropical terrains in the Amazon and in an island environment of the Indian Ocean. With regard to the semi-arid zone of West Africa, the related work integrates the territory scale and is therefore discussed in the last part of this sub-chapter.

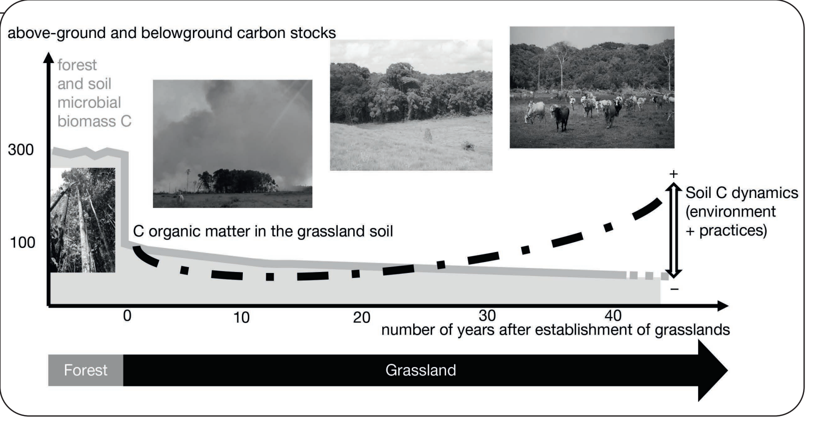
The Amazon is an emblematic region for sustainability issues related livestock grazing systems. Efforts to combat deforestation continue to be a priority for preserving carbon stocks and other ecosystem services provided by forests such as biodiversity and the maintenance of rainfall regimes. However, this core principle must also be combined with sustainable management of areas converted to grazing land to establish climate change mitigation strategies.

In the French Amazon (Guyana), measurement and observation devices on carbon fluxes and stocks have been established in deforestation-derived grassland systems (Blanfort and Stahl, 2013; Blanfort *et al.*, 2015a). Cattle farming systems are extensive (~ 1 LSU/ha); feed is provided solely by cultivated grasslands (mainly Brachiaria humidicola grass), with low input use. This “ranching” type of management is widespread throughout the Amazon region.

The research setup consists of an innovative combination of two approaches. Measurements of net gas exchanges of CO_2 between the atmosphere and the grazing ecosystem are carried out in 2 grassland plots equipped with flow towers (turbulent correlation method). Quantification of the rate of carbon fixation/emission by the grasslands leads to net annual carbon profiles integrating all ecosystem biological processes and the impact of management practices (such as rest periods and stocking rate). In addition, grassland carbon storage is estimated by measuring soil carbon stocks over a chronosequence (4 control forests and 24 grasslands aged from 6 months to 36 years). Samples are taken at 1 meter depth of, in order to capture deeper soil horizons than the usual standard.

The results demonstrate that deforestation-derived grasslands in Guyana function as carbon-storing ecosystems (Figure 3.3), provided they are sustained over several decades (Stahl et al., 2017). After around twenty years, storage potentially amounts to 1.27 ± 0.37 tC/ha/yr, while the neighbouring native forest stores 3.23 ± 0.65 tC/ha/yr (Guyaflux INRAE device). Carbon accumulation in stabilized form occurs in the lower horizons, between 0.3 and 1 m depth (Stahl et al., 2016). This storage level constitutes a very significant mitigating potential linked to the maintenance over time of a productive and non-degraded (dense, non-eroded) grassland cover developing on soil that retains good physico-chemical qualities. This includes encouraging the establishment

Figure 3.3. Reconstructing soil carbon stock dynamics after the conversion of Amazon rainforest to a grazing system.



of grassland with a mixture of grasses and legumes to permit nitrogen inputs into the soil. The implementation of a rotational grazing system and an adjusted stocking rate is also essential to maintain an active and covered biomass throughout the year. The maintenance of vegetation by slashing is clearly preferable to clearing by fire, which leads to nitrogen losses and a modification of biological activity. It is also noted that conditions favourable to the accumulation of carbon in the organic matter of soils grazed also promote the production of a good quality forage resource.

If the strategy of sequestering carbon in the soil is a proven mitigation potential for livestock grazing systems, it also has limitations.

Soil stocks are extremely fragile and can be altered in a number of ways: by a change in land use, temperature rise, or by various fertilization or other tillage practices. In order to produce references in the tropics, research projects on the island of Reunion are specifying the modalities and potential for carbon sequestration of permanent grasslands on volcanic and sandy soils.

The diachronic device extends over a period of nearly 15 years (2004 to 2019), based on an intensive organic and mineral fertilisation trial on 4 m² microplots in permanent grasslands used for mowing. It was conducted on 3 sites:

- one site on sandy soil in a coastal zone in a tropical climate (arenosol) initially very low in carbon (20 tC/ha on the 0-15 cm horizon),
- and two sites at altitude (900-1,500 m) on volcanic soils (andosol) initially very rich in carbon (80-100 tC/ha).

Fertilisation rates were up to 70 m³/ha of liquid manure and 12 t/ha of compost per harvest.

The results indicate that the ratio between the increase in soil carbon and the carbon provided by fertilization is greater for compost than for slurry: from 16% to 28% for compost and from 2% to 8% for slurry. This difference is due to the nature of the carbon provided. Compost carbon is less likely to volatilize, the volatile part being partly lost during the composting process. Globally, a significant and substantial increase in soil carbon stock is measured each year in response to organic matter inputs in the form of manure and compost, ranging from 0.32 and 2.85 tC/ha/yr. Carbon sequestration was found to be greater on sandy soils that were initially poorer in organic matter and therefore in carbon. However, the increase observed on andosols is still significant, with an accumulation of several tons of carbon over the entire period, whereas these andosols, which are by nature rich in carbon, are considered to be "saturated" in carbon (Zieger *et al.*, 2018).

From reference acquisition to the development of energy and carbon balance at the farm scale

In contexts based on closed and clearly delimited management spaces, the "farm" is a relevant scale for actions aimed at climate change mitigation and adaptation. It integrates the "plot" and "herd" scales, which in turn integrate the biological, ecological and physiological processes taking place at smaller scales, in the plants, the soil and the animal. The farm is the management unit where decisions related to practices are made by clearly identified decision-makers: the farmers, their families and their employees. It is therefore a functional level, relevant for drawing up assessments that will guide strategic choices and the practices implemented.

The diagnostic tools that characterise the levels of energy consumption and GHG emissions at this level of organisation of the "farm" come in different types: calculators, protocols, user guides and models (Box 3.2). Construction and mobilisation procedures for these tools were conducted in two French tropical overseas territories: an island situation on Reunion and one in the French Amazon in French Guiana.

T**he carbon calculator tool "PLANETE" designed in mainland France and validated by the European Energy Agency (The AgriClimateChange Tool ACCT)**, was first adapted to the context of the island of Reunion to assess energy consumption and GHG emissions on livestock farms in this department (Thévenot *et al.*, 2011). The high human density, combined with significant effluent and fodder production, renders the environmental assessment of farms in relation to climate change crucial.

Based on this tool, renamed Planète Mascareignes, 235 energy assessments have been carried out on the island of Reunion on all animal production on the island (Vigne, 2007; 2009a; 2009b; Vayssières *et al.*, 2010; 2011b). These results can be used to calculate the environmental cost of insularity, defined as the additional energy consumption and GHG emissions induced by the overall transport costs imposed by the island's isolation and the decision to develop livestock production systems on the island of Reunion that require high levels of imported inputs. On the whole, this cost is high because it is equal to or greater than 20%, both in terms of energy consumption and GHG emissions. In addition, these efficiency and inefficiency indicators provide a comparison of local livestock production (Table 3.1).

Table 3.1. Techno-environmental performance of the various animal productions on the island of Reunion in 2007 assessed at the farm level including resource consumption and indirect GHG emissions related to input consumption (Vayssières *et al.*, 2010).

Animal production	Feed conversion efficiency	Energy efficiency	Share of animal feed-related NRE consumption	Global GHG Emissions	Coefficient of variation of variation Coefficient of variation	Share of enteric emissions in total GHG emissions
	(kg concentrate feed consumed/kg product)	(kg gross energy produced/ kg NRE consumed)	(%)	(kg CO_2 eq animal protein produced)	(%)	(% CH_4)
Milk (dairy farm)	0.79	0.37	55.3	87.3	24.5	26.2
Meat (cattle breeder farm)	4.00	0.19	31.9	239.7	66.5	65.5
Meat (cattle fattening farm)	5.48	0.42	53.3	104.7	27.3	40.1
Meat (pork)	3.23	0.62	77.0	35.9	18.7	6.1
Meat (poultry)	2.19	0.36	75.3	25.9	15.6	1.8
Meat (rabbit)	3.99	0.15	58.8	83.2	28.8	2.3

NRE: Non renewable energy.
GHG: Greenhouse gas.

The production of 1 kg of beef protein has the higher impact in terms of GHG emissions, followed by cow's milk, while chicken and pork production have the lowest impacts. Regardless of the type of protein produced, animal feed is the main source of fossil energy consumption (>30%). The differences are primarily explained by three factors: feed conversion efficiency, reproduction and mortality rates, and methane conversion rates between ruminants and monogastrics.

On the face of it, these findings would encourage the substitution of red meat by white meat, in accordance with other studies (De Vries and de Boer, 2021) and which is now widely relayed in human nutrition recommendations for environmental reasons, in addition to the nutritional arguments produced by the medical world. However, other elements must take account of food choices, notably the "feed-food" competition. Compared to ruminants, monogastric animal rations contain a higher proportion of products that can compete with human food (Mottet *et al.*, 2017), such as cereals, and that humans could consume directly and more efficiently. This is not the case for forage grasses, for which only ruminants are efficient. In addition, the development of beef cattle farms on the island of Reunion has been accomplished through the establishment of grass breeding systems in vast areas of the territory which, during the 1970s and 80s, were in the process of being depopulated with a risk of closure by wasteland and the invasion of exogenous invasive plants. This has resulted in a revival of economic activities in these rural areas of altitude that would not be valorized by other activities than livestock.

In all sectors combined however, there is considerable room for improvement, for example by favouring sources of supply closer to the island of Reunion. It is also necessary to reduce the distribution of concentrated feed for ruminants. This can be achieved mainly by improving the quality of the fodder supplied (by replacing part of the concentrates) and by improved monitoring of reproduction (reduction of the calving-to-calving interval).

In French Guiana, the planned transition of Guyanese agriculture requires contextualized assessment tools. The objective is to establish energy and GHG emission diagnoses with the aim of identifying action levers adapted to the farms in this territory.

The objective is to identify more efficient and environmentally effective farming systems in a territory that is emblematic of global change. The "French Amazon" is indeed an emblematic situation. French Guiana is the only French department that has seen an increase in the utilized agricultural area (UAA) and the number of farms. However, despite its continental and non-insular location, this territory remains very dependent on food imports; the coverage rates are almost zero for milk and 17% for beef. The expected doubling of the population in French Guiana by 2030 will lead Guyanese decision-makers to make decisive choices as regards territorial development. A strong endogenous growth of certain agricultural sectors such as livestock is intended. This implies the implementation of a development plan for the ruminant sector consistent with forest preservation (95% of the territory, 50% of the carbon of French forests) and with the framework of European climate commitments. The development of already deforested areas (sometimes not exploited) and the implementation of grassland systems with a higher stocking rate are mentioned. Moreover, unlike other more industrialised regions of Europe, the agricultural sector is much more important in the carbon balance of this department (23% of annual changes in forest land use).

In order to have local references, an Energy/Carbon balance tool was adapted in a study conducted in 33 farms that were subject to an Energy/Carbon diagnosis including 15 beef farmers (Dallaporta, 2016). The results indicate that energy efficiency and GHG emissions vary according to the types of livestock systems and their degree of development (Figure 3.4).

We refer to a typology of the Livestock Institute (2014):
• "cattle farmers" correspond to small-scale structures where the farm manager is multi-active,
• "the large land owners" are catlle farms of over 200 ha that have completed their land acquisition phase,
• the farmers with land reserves constitute an increasing group to the type "large land owners".

The energy and GHG emission diagnostics established on these Guyanese grass-fed farms are also highly dependent on the calculation method chosen (Figure 3.4). Expressed per unit produced (tonne of meat), the efficiencies are twice as low as the means observed in mainland France (Table 3.2). This can be explained by the fact that livestock grazing systems in French Guiana are characterised by almost exclusive grass feeding, fodder species of lower value and with high seasonal variability, as well as low stocking rates. Conversely, the efficiency ratio calculated per unit area is highly favourable in French Guiana, with a greater number of hectares available per animal, which can store more carbon in the soil, without significant consumption of non-renewable energy (only solar energy is used for the growth of grasses, combined with natural rainfall). Consequently, French Guiana illustrates very effectively the potential of livestock grazing systems in the humid tropics to produce quality meat (on grass), with environmental costs that are much lower than the more intensive systems common in temperate area.

Figure 3.4. GHG emissions according to the energy balance of grassland cattle systems in Guyana (2013). A: per ton of live weight sold; B: per hectare of utilized agricultural area (UAA).

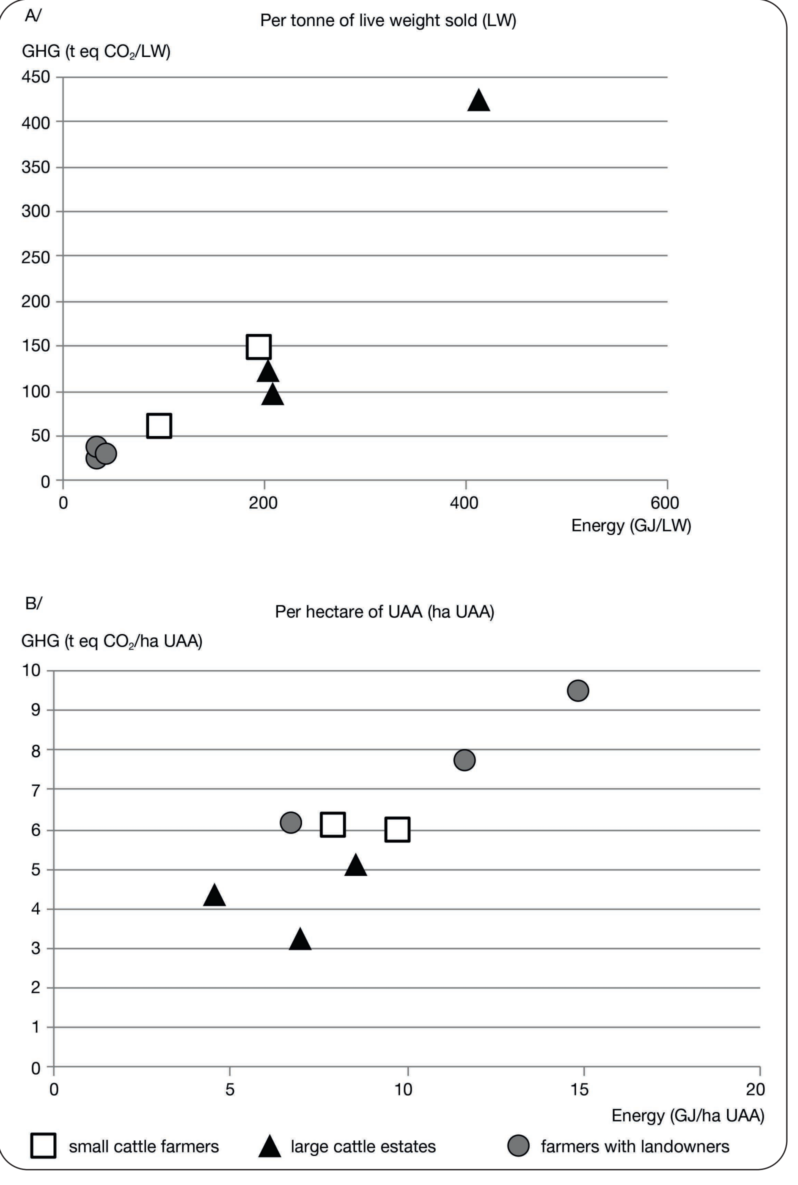


Table 3.2. Comparison of energy and GHG emission balances in French Guiana and metropolitan France (Bordet *et al.*, 2011; http://agribalyse.ademe.fr/).

Energy efficiency				GHG emission efficiencies				
Per unit produced		Per unit of area		Per unit produced			Per unit of area	
ACCT DOM®	Planete®	ACCT DOM®	Planete®	ACCT DOM®	Agribalyse®	Planete®	ACCT DOM®	Planete®
French Guiana	Mainland France	French Guiana	Mainland France	French Guiana	Mainland France	Mainland France	French Guiana	Mainland France
GJ/unit	GJ/unit	GJ/ha	GJ/ha	t eq CO2/ unit	t eq CO2/unit	t eq CO2/ unit	t eq CO2/ ha	t eq CO2/ha
73	30	7	16.6	27.1	14.4	12.8	4.6	5.6

Box 3.2. AgriClimateChange Tool (ACCT), an energy and carbon balance tool adapted for the French overseas departments - example of its adaptation to French Guiana in collaboration with Solagro (http://www.solagro.org).

Vincent Blanfort

ACCT provides a "technical" quantified inventory of the situation, covering an overall analysis of:

- the Farm energy dependency: non-renewable energy consumption, production and consumption of renewable energy (indirect energy used for purchases of feed, fertilizer and equipment),

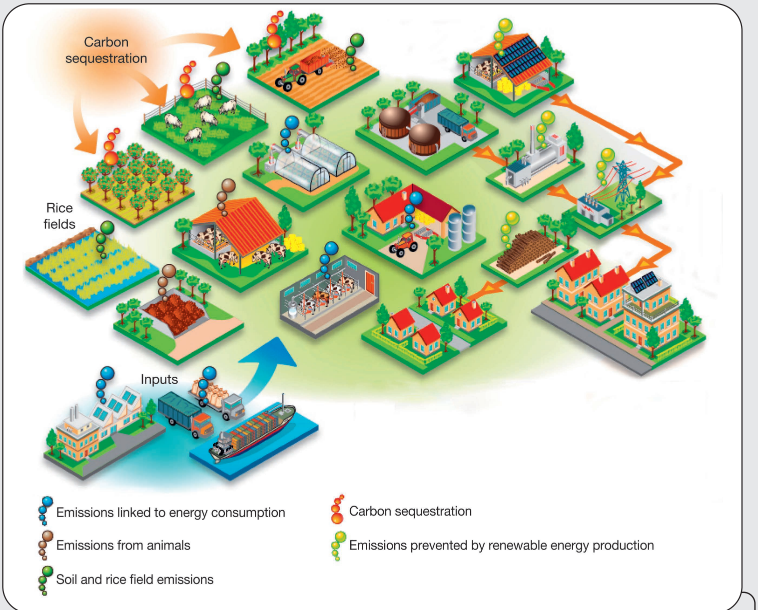
- greenhouse gas emissions: GHG emissions on the farm (total, per item and additional production/storage of carbon in the soil),

- nitrogen environmental indicators: water risks (overall balance on the "soil/UAA" level).

This is an analysis by production house to identify the most energy-consuming and GHG-emitting items.

Finally, this tool makes it possible to identify proposed improvement actions quantified in terms of energy, GHG and cost savings (Figure 3.5).

Figure 3.5. A schematic diagram of the GHG emission sources, carbon stock changes and GHG emissions prevented by renewable energy production taken into account in ACCT.



Source: https://solagro.org/travaux-et-productions/outils/acctool-acct-simplified-version-acct-dom.

ACCT is the result of a development process based on tools and reference systems that have mobilised various stakeholders since 1999 in conjunction with Solagro and CIRAD for the French overseas departments:

- Planète® (1999-2010), creation of references by farming system (RefPlanete 2010);

- Dia'terre® (2010), a national Ademe tool for farm energy and waste management diagnosis; (ADEME: French Energy Agency)

- ClimAgri® (2009), Ademe tool for energy and waste management diagnosis on a territorial scale (Solagro);

- Life+ AgriClimate Change programme - http://www.agriclimatechange.eu/, (2009-2013);

- ACCT-DOM® (since 2014), support for energy investment policies on farms in the French overseas departments (Antilles, Reunion);

- ACCT-DOM® in Amazonia in French Guiana (2017) and Brazil (2021) implemented by Cirad.

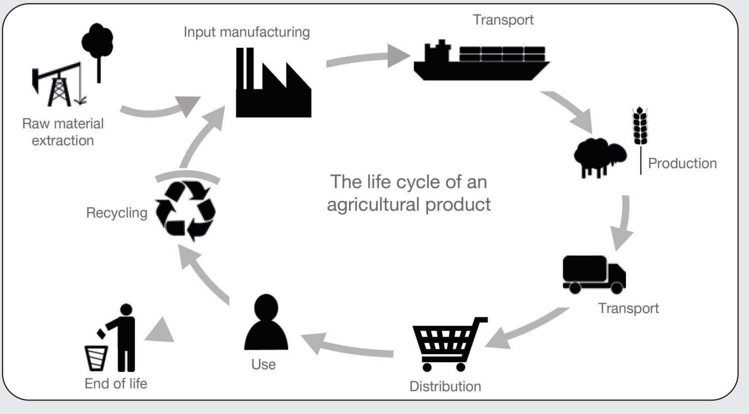
Box 3.3. Seeing beyond the herd or the farm through the "life cycle" approach.

Mathieu Vigne

For several years now, environmental assessments no longer focus solely on the direct impacts of livestock activities, i.e. the impacts that take place on the farm. They are based on the "life cycle" approach, which defines all the processes that take place upstream of the system, mainly to produce inputs, and downstream, to bring the system's product(s) to the consumer and to treat the waste generated by its consumption (Figure 3.6). This approach can be applied to measure the indirect environmental impacts linked to the production and consumption of the product. For livestock production, the "emblematic" indirect impact concerning greenhouse gas emissions is, for example, the impact on deforestation in South America linked to the consumption of soya cake by livestock systems in Europe.

This approach is all the more important as it enables the design of practices that jointly reduce impacts both locally (so-called "direct") and elsewhere (so-called "indirect"), and so avoid "false good ideas" such as relocating feed production and breeding (farmer cattle, fattening cattle), which can lead to higher transport-related impacts (see case study on livestock farming on the island of Reunion).

Figure 3.6. The life cycle of an agricultural product.



Applied to fossil energy consumption and greenhouse gas emissions, this approach has been implemented by UMR Selmet researchers, in particular on numerous dairy and beef cattle systems in a variety of contexts in South and Central America (Brazil, Costa Rica, Guyana), Africa (Burkina Faso, Burundi, Egypt, Mali, Democratic Republic of Congo, Zimbabwe) and the Indian Ocean (Reunion, India). This holistic approach also allows us to make accurate comparisons of very diverse systems in terms of the level of intensification and utilisation of grazing. Our work shows that the importance of "indirect" emissions is lower for tropical systems in developing countries largely dominated by low-input systems (Vigne *et al.*, 2015).

Towards carbon-neutral grazing livestock territories?

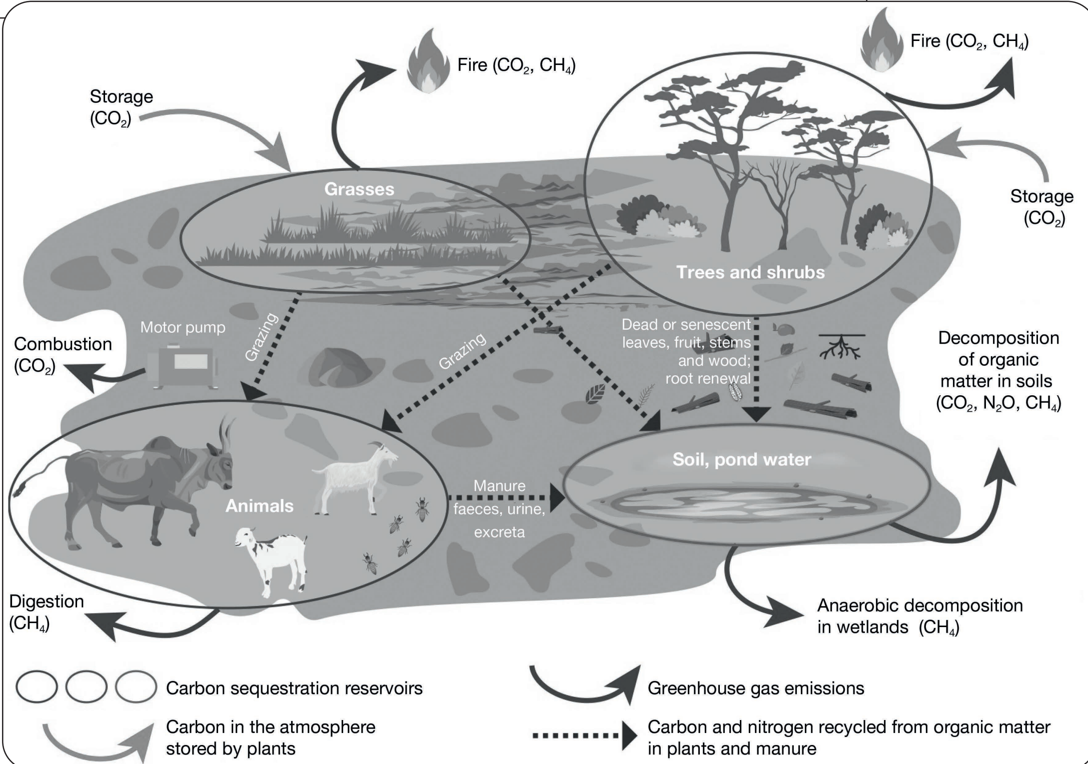
The farm-scale assessments described above relate to well-defined areas (the boundaries of the farm) and whose management is based on also well-defined (usually individual) decision-making systems. They are poorly adapted to systems open to input imports (Box 3.3) or to community-based resource management, which are also characterised by temporal variability (seasonality) and spatial heterogeneity of ecological processes of GHG emissions or carbon sequestration. This is the case for livestock farming in the Sahel, which is traditionally discussed in the debate on global warming, but whose impact has never been precisely assessed because pastoral ecosystems are complex, poorly conceptualised and not assessed from this point of view.

An original system adapted to these variabilities has made it possible to address these issues in a pastoral area of the Senegalese Ferlo (Assouma et al., 2019). It integrates the different compartments of the ecosystem (animals, soil, vegetation) and measures all components of the carbon balance at the landscape level (Figure 3.7). The catchment area of the Widou borehole (circle of 30 km diameter around the borehole, i.e. 706 km²) in the sylvopastoral region of the Ferlo Nord was chosen as the spatial unit of analysis.

The results indicated that the carbon footprint of the area is in balance, although it varies according to location and season. In this grazing ecosystem, one hectare emits 0.71 tonnes of carbon equivalent per year and sequesters 0.75 tonnes: it therefore stores the difference, i.e. 40 ±6 kilograms of carbon equivalent. The carbon balance is thereby neutral: carbon sequestration in the trees, shrubs and soils offsets the GHG emissions of the animals linked to their feed and the deposit of their droppings. At a more detailed level within this area, spatial variation can also be observed in relation to livestock farming practices. Grassland, shrubland and woodland, where animals move to graze, are locations where carbon sequestration prevails. Conversely, resting areas near campsites and the edges of water points, which are subject to a lot of dung and where vegetation is scarcer, are emitters because of the high GHG emissions at ground level during the rainy season. The seasonal variation of the carbon balance could also be measured. In the rainy season, the ecosystem emits much more GHG than it stores carbon - animals and ponds with their surroundings being the main sources of emissions. Conversely, in the dry season, the ecosystem stores - as dung and grasses are buried in the soil by trampling animals - and the large GHG fluxes to soils that occur in the rainy season decrease considerably as soil moisture levels fall.

By highlighting the spatial and temporal heterogeneity of emission processes and carbon sequestration, mitigation options can be proposed for the various landscape units:
- developing and maintaining water troughs near boreholes and ponds to avoid droppings being deposited directly into the water;
- making better use of the natural vegetation that grows each year in order to ensure a longer availability of fodder resources with the delimitation of temporary set-asides accompanied by a good firebreak system and the constitution of fodder stocks (straw/hay);

Figure 3.7. Simplified model of GHG emissions and carbon storage in a Sahelian pastoral territory (Assouma *et al.*, 2019).



The ecosystem approach to carbon balance is based on this model. A spatially explicit and monthly measurement protocol was implemented from May 2014 to October 2015 to estimate GHG emissions (enteric methane from livestock, nitrous oxide and methane from soil, ponds and termites, fuel consumed, fires) and carbon sequestration (above-ground and below-ground biomass from trees and shrubs, soil and animals).

• by better use of animal waste to produce organic manure for fertilising garden soils or fuel in biodigesters for the surrounding populations.

In view of the seasonality and interannual variability that condition the functioning of these ecosystems, as well as the livestock system mobility, this ecosystem-based approach to carbon balance still needs to be consolidated by measurements over several years and by diversifying the sites. The multiplication of measurements of GHG emissions and carbon sequestration potential would consolidate these results and enable integrating these references into the IPCC guidelines relating to pastoral and agropastoral systems, for which there is still insufficient data, in particular the offsetting of emissions by carbon sequestration potential. The approach could also help to compare different types of tropical landscapes or agricultural territories, more or less densely grazed, where livestock farming is integrated with protected areas, specialized agricultural areas, etc.

⁂

This chapter has mobilised the results of several field research schemes on livestock grazing systems in tropical areas. The elements presented illustrate the relevance of the concept of environmental efficiency to address the issue of climate change, but also the difficulties it raises in tropical and Mediterranean regions.

To conclude, it is essential to stress the lack of sufficiently numerous and solid scientific references, such as those available in the North. Researchers have shown that the direct transposition to the South of reasoning, or even measurements carried out in the North, is unsuitable. In fact, biological and biochemical mechanisms do not follow the same rhythms, nor have the same intensity: photosynthesis, metabolisms, decomposition, among others, are very different in the tropics. Furthermore, livestock systems do not function according to the same logics, because of specific constraints and opportunities, such as land tenure or access to land, decision-making systems, access to services and inputs, etc. A first conclusion is therefore the importance of continuing this work on producing references, in order to improve evaluations and avoid the need to resort to transpositions of North-South reasoning.

Beyond the lack of scientific references that they highlight, these examples show the potential of tropical grassland systems to meet climate change challenges. Whether at the fine scale of plots and soil-plant relationships, at the intermediate scale of farms or at the broader scale of landscapes and territories, we highlight interesting mechanisms for soil carbon sequestration, reduction of methane emissions by cattle and energy consumption. These mechanisms depend on good practices at all levels, hence the interest in producing multi-criteria or even multi-level evaluation or simulation tools. It is important to note that these potentials concern both relatively extensive grassland systems such as in French Guiana, where grassland management makes it possible to constitute carbon sinks up to one metre deep, and more intensive systems such as those on the island of Reunion where organic matter inputs play a role not only in fertilising fodder plants, but also in sequestering them in the soil.

The pursuit of efficiency to support the agroecological transition in livestock systems

Fabien Stark, Paulo Salgado, Stéphanie Alvarez, Claire Aubron, Ida Bénagabou, Mélanie Blanchard, Myriam Grillot, Sophie Plassin, René Poccard-Chapuis, Jonathan Vayssières, Mathieu Vigne

As mentioned in the previous section, the evaluation of the contribution of livestock systems to climate change issues, through the concept of efficiency and the various indicators derived from it, has made it possible to identify promising grassland livestock practices to meet the combined challenges of climate change and food security. Agroecology is also one of the avenues mentioned in the scientific literature and adopted by national and international public policies to meet the objectives assigned to agriculture in terms of sustainable development (SDGs), climate change, food security, pollution reduction and even poverty reduction (FAO, 2018b). Agroecology can effectively be defined as a set of agricultural practices aimed at mobilising biological and ecological processes for the production of goods and services.

Despite the central role of livestock in the processes of transferring and completing nutrient cycles, scientific work on the principles of agroecology applied to livestock is relatively recent (Dumont et al., 2013). Nevertheless, grass-fed and mixed farming-livestock systems, which are mainly found in Mediterranean and Tropical environments, can apply the principles of agroecology to meet the challenges of agriculture. These systems exploit and manage a diversity of natural resources that do not conflict with human nutrition (grazing resources) and mobilise the complementarities between crop and livestock through biomass recycling (by-products, organic manure). These practices ultimately contribute to the closing of nutrient and biomass cycles in order to reduce the use of inputs, recycle by-products and reduce pollution, both at the farm and territorial levels.

To support the agroecological transition of livestock systems, several livestock practices based on these principles can be deployed. Whether it involves animal feeding practices, manure management and organic manure production, or fodder resource management, a whole range of levers can be mobilised by livestock farmers to achieve this agroecological transition. Based on the concept of efficiency, i.e. the ratio between goods or services generated and mobilised resources, several dimensions of the agroecological transition can be considered. They help to design and assess livestock practices and systems to make better use of mobilised resources and increase the production of goods and services.

In this chapter, we will illustrate this principle with recent research results on grass-fed and mixed farming-livestock systems, focusing on nutrient flows.

Closing cycles to improve the biochemical efficiency of livestock systems

The work presented here relates to integrated crop-livestock system (ICLS) practices at the farm level, through the analysis of energy and nutrient flows, with a view to closing biogeochemical cycles. To adapt to the increasing scarcity of resources and reduce the negative externalities associated with intensive production models, while meeting the demands of an expanding world population, farmers must produce more and better. Based on the principles of agro-ecology applied to mixed crop-livestock systems, efficiency is one of the main properties required for these diversified systems (Bonaudo *et al.*, 2014).

A sustainable production system will require an efficient use of local resources and inputs to reduce negative externalities. The quantities of nutrients (especially nitrogen) - including inputs to which many farmers in developing countries have little access - must be used wisely to improve farm efficiency. This means improving recycling and therefore conserving nutrients in the system.

Biomass management and organic manure production of agropastoral farms in the West African savannahs

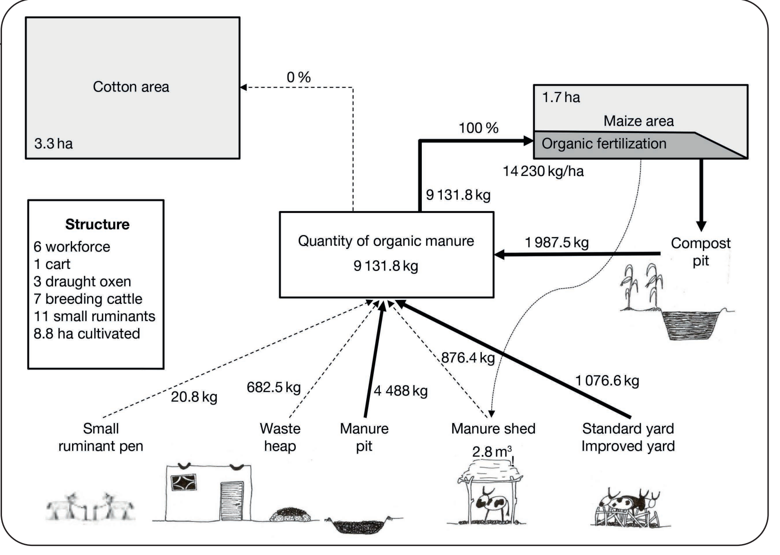
Work carried out in the West African savannahs (Mali and Burkina Faso) focused on characterising organic manure production and management practices, which are used to recycle biomass to fertilise soils, a recurrent problem in all the so-called cotton-growing (sub-humid) areas of the region (Blanchard *et al.*, 2013).

The analysis of biomass recycling to produce manure was carried out by characterising practices at each stage of the cycle, measuring their efficiency (carbon and nitrogen) and analysing the recycling/loss relationship from the collection of crop residue and animal dung to the application of manure and compost in the field (Figure 3.8).

This work has identified practices that can improve the proportion of crop residue and animal manure converted into organic manure. These practices improve the efficiency of nitrogen recycling, regardless of the size and structure of the farm. To promote this type of practice, conventional organic manure production structures are built, such as on-farm pits and improved yards. Other so-called innovative structures are used to produce organic manure from the field to the farm (pit in the field, improved pens with cotton stalks as bedding, pens without bedding, animal shelters). Farmers with innovative practices diversify the modes of organic manure production and distribute them between the field and the farm, mobilising biomass where it is produced, with little investment in labour and transport. As a result, they make more efficient use of crop residue and animal waste, increasing the efficiency of nitrogen recycling (23 and 31% compared to 16% of recycled biomass for the less innovative).

Furthermore, the recycling rate of biomass on farms is still limited and there is room for improvement. The estimated recovery of animal manure as organic manure is between

Figure 3.8. Biomass recycling and organic manure production by farmers (Blanchard, 2010). A schematic representation of nutrient recycling through the production and use of organic manure on a typical West African farm, based on organic manure management methods.



38 and 50% and between 8 and 16% of plant biomass currently recovered as organic manure. The recycling efficiency of carbon and nitrogen is also limited, with nutrient losses through leaching and gaseous emissions that are still significant and that lead to recycling efficiency rates of between 8 and 11% for carbon and 16 and 37% for nitrogen.

Consequently, even if the production of organic manure makes it possible to improve the recycling of biomass on these farms, the recycling of biomass is far below that required to maintain the fertility of cultivated soils, the fertilisation of which is currently supported by fertiliser use. Given the limited availability of these nutrients, improving the recycling efficiency of these nutrients must be considered beyond the farm level to sustain the level of soil fertility.

Impact of crop-livestock integration practices on agroecological performance: a comparative study of Latin-Caribbean farms

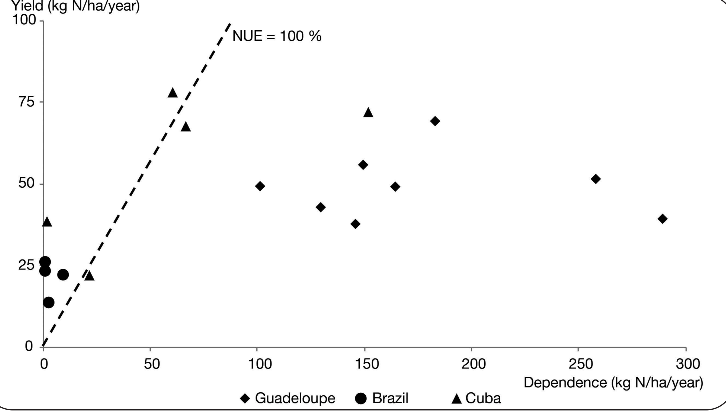
In order to assess the contribution of nutrient cycling to the so-called agroecological performance of mixed crop-livestock systems, a comparative analysis of crop-livestock integration practices between farms in three Latin-Caribbean territories (Guadeloupe, Brazilian Amazon and Cuba) was carried out in the framework of a PhD thesis (Stark *et al.*, 2018). The underlying hypothesis is that diversified and integrated farming systems mobilise biological and ecological processes that allow them to be more effective from an agroecological point of view, in particular in terms of efficiency.

For this purpose, the crop-livestock integration practices implemented on some fifteen farms in these three territories were translated into nitrogen flow networks. The ecological network analysis (ENA), a flow network analysis method used in ecology, was used in the framework of this project to obtain a systemic vision of the nitrogen dynamics at the farm level (Box 3.4). Each farm was modelled as a matrix of flows, and a set of indicators characterising this network of flows (intensity and organisation) and its properties (resilience, dependence, productivity and efficiency) could be calculated. In this case, efficiency corresponds to the ratio between productivity and autonomy (output/input).

When analysing the relationship between productivity and dependency in farms, various efficiency profiles can be identified, partly linked to the crop-livestock integration practices implemented and partly to their level of intensification. Depending on the farms, and to a lesser extent the study regions, the productivity ranges are very wide, varying from 13 to 72 kg N/ha/year (animal and plant products combined) and dependency levels between 1 and 289 kg N/ha/year (all inputs). The resulting efficiency actually presents contrasting profiles (Figure 3.9):

• Extensive systems with low input consumption (dependence ≤ 22 kg N/ha/year) and low productivity (≤ 39 kg N/ha/year) implementing a variety of integration practices of

Figure 3.9. The relationship between productivity and dependency indicators, and resulting efficiency profiles (Stark *et al.*, 2018).



Efficiency profiles of 17 farms in three territories (Guadeloupe, Brazil, Cuba) based on their degree of dependence (expressed as kg N/ha/year originating from outside the farm) and their level of productivity (expressed as kg N/ha/year of products sold or consumed off farm). The dotted line corresponds to the nitrogen use efficiency (NUE) of 100% (one unit of nitrogen produced for one unit of nitrogen consumed) for the case studies at the lower end of the range efficiency levels below 100% and at the higher end efficiency levels above 100%.d'efficience supérieurs à 100 %.

low intensity. These are farms with efficiency levels above, or even well above at 100% (between 103 and 3,303%), ultimately taking into account a low recourse to inputs from outside the farm, and therefore potentially over-consuming natural resources, which questions the renewal of the biomass and soil fertility associated with these systems.
• More productive intensive systems (between 38 and 72 kg N/ha/year) and highly input intensive (dependence ≥ 102 kg N/ha/year), implementing few low intensity integration practices. These are the least efficient farms (14-47%).
• Systems with higher levels of productivity (≤ 68 kg N/ha/year) and with intermediate levels of dependency (between 60 and 66 kg N/ha/year), implementing a variety of integration practices of significant intensity. These are farms with efficiency levels close to 100%, consuming as much input as exported products.

The multivariate analysis of variables from which these results were derived (Stark *et al.*, 2018) also assessed correlations between farm-livestock integration practices and efficiency. Productivity and integration intensity are partially correlated, while, contrary to our hypotheses, integration intensity and dependence are not correlated. Consequently, it seems that in the situations characterised, integration practices do not appear to be substitutes for the use of inputs (from a quantitative point of view with regard to nitrogen), but that they are complementary and in fact contribute to the overall productivity of the systems studied. Efficiency, as used in this study, therefore made it possible to identify certain farm profiles according to the practices implemented, and to question the expected performance of these systems as well as their sustainability.

Impacts of crop-livestock integration on the energy efficiency of Sahelo-Sudanese agroecosystems: the case of Koumbia in Burkina Faso

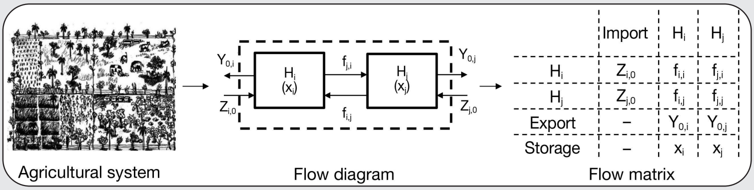
Mixed crop-livestock systems in the West African savannah (Mali and Burkina Faso) tend to integrate livestock and crop activities. While much work has been conducted on the capacity of ICLS to improve the resilience and productivity of these systems, little has been undertaken to analyse its contribution to the mitigation of environmental impacts such as fossil fuel consumption.

Box 3.4. Nutrient flow network analysis for livestock system performance assessment: *ecological network analysis*.

Fabien Stark

Ecological network analysis is an input-output analysis method that consists of a quantitative representation of the interactions between components of a system and between these components and their environment. In order to carry out this type of analysis, two preliminary steps are necessary: the conceptualisation of the system studied in a flow diagram and the modelling of the flow network in a flow matrix in order to be able to carry out the actual quantitative analysis (Figure 3.10).

Figure 3.10. Summary diagram of the steps involved in matrix modelling of the structure and functioning of the systems studied (Stark, 2018).



In the context of the work carried out, two groups of indicators were developed for analysis, one to characterise crop-livestock integration, the other to assess the agroecological performance of mixed crop-livestock systems (Table 3.3). The indicators for characterising crop-livestock integration involve the structure and the intensity of the flow network. These indicators enable the characterisation of crop-livestock integration according to the complexity and the intensity of nutrient transfers between the compartments. The performance indicators refer to the four principles of agroecology as defined by Bonaudo *et al.* (2014): efficiency, resilience, productivity and dependence (corollary of self-sufficiency).

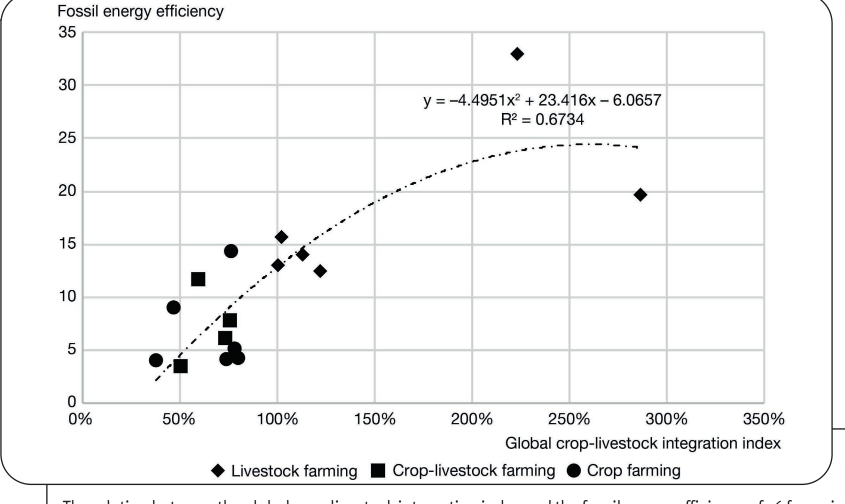
Table 3.3. Crop-livestock integration indicators and performance indicators.

Crop-livestock integration indicators	Performance indicators
System activity $TST = \sum_{i=1}^{n} T_i$	Productivity $\sum_{j=1}^{n} Y_{0,j}$
Circulating flow $T_i = \sum_{j=1}^{n} f_{i,j} + Z_{i,0} - (x_i)$	Dependency $\sum_{i=1}^{n} Z_{i,0}$
ICLS intensity $TT = \sum_{i=1}^{j=n} f_{i,j}$	Efficiency $\sum_{j=1}^{n} Y_{0,j} \Big/ \sum_{i=1}^{n} Z_{I,0}$
Average mutual information $AMI = k \sum_{i=1}^{n+2} \sum_{j=0}^{n} \frac{T_{ij}}{T_{..}} \log_2 \frac{T_{ij} T_{..}}{T_{i.} T_{.j}}$	Overhead $\Phi = -\sum_{i.j} T_{ij} \log\left(\frac{T_{ij}^2}{T_{i.} T_{.j}}\right)$
Statistical uncertainty $H_r = -\sum_{j=0}^{n} \frac{T_{.j}}{T_{..}} \log_2 \frac{T_{.j}}{T_{..}}$	Development capacity $C = -\sum_{i.j} T_{ij} \log\left(\frac{T_{ij}}{T_{..}}\right)$
Organisation of the flow networkx AMI / H_r	Resilience Φ / C

A PhD thesis (Bénagabou *et al.*, 2017) aimed to compare various levels of ICLS on the scale of 16 farms in the commune of Koumbia (western Burkina Faso) and their impact on their fossil energy consumption. To accomplish this, indicators describing ICLS practices were calculated: coverage of animal traction needs (CBTA), coverage of organic manure needs (CBFO) and coverage of fodder needs (CBF). These indicators were then synthesised into an overall ICLS indicator and analysed with respect to the fossil energy efficiency of the farms, considered as the ratio between the gross energy produced and the fossil energy consumed directly and indirectly.

The results indicate that the three pillars of ICLS lead to a better overall efficiency in the use of fossil energy consumed (Figure 3.11). This is particularly true for farmers who make great efforts to ensure that their organic manure needs are well covered, thanks to a high animal stocking rate. Generally speaking, the joint improvement in ICLS and fossil energy efficiency is mainly explained by a substitution of mineral fertilisers by organic manure and a better use of crop residue to feed the herd, thereby leading to a reduction in the synthetic input consumed on the farm and therefore in indirect fossil energy consumption.

Figure 3.11. Crop-livestock integration and fossil fuel efficiency (Bénagabou *et al.*, 2017).



The relation between the global crop-livestock integration index and the fossil energy efficiency of 16 farms in western Burkina Faso according to their dominant activity: livestock farmer, crop-livestock farmer or crop farmer.

Increasing biomass and nitrogen recycling on dairy farms in the Malagasy highlands

Research conducted in Madagascar (Alvarez *et al.*, 2014) focused on characterising nutrient flows (in particular nitrogen) at the scale of mixed farms in order to identify the influencing factors at each stage of the transfer cycle. The objective was to identify whether certain Integrated Crop-Livestock System (ICLS) practices create more productive and sustainable systems. This research also used the Ecological Network Analysis (ENA) with the objective of exploring alternative nutrient management scenarios.

Several farms illustrating the diversity of crop-livestock systems in the Highlands of Madagascar, according to a typology based on cropping practices and resource and effluent management, were used as a basis for the study. Four types of mixed crop-livestock farms were identified:

- (T1) large livestock farms (>8 animals) with European cattle breeds and significant diversification with poultry and swine farming,
- (T2) farms with fewer dairy cows (approximately two) and significant diversification with swine farming,
- (T3) farms with small areas (<60 ares) on hillsides and dairy animals fed almost exclusively on ad libitum fodder, without grazing
- and (T4) farms with one or two zebu crossbreeds, with low milk production and very few fodder crops.

Regardless of the type of farm, crop-livestock integration practices can be observed. They correspond to the transfer of fodder and crop residues from the cropping system to livestock systems and to the contribution of manure for crop fertilisation. The farms studied were represented as networks, where the links between compartments represent biomass flows within the farm.

Most of the biomass and nutrient flows were quantified thanks to on-farm measurements (biomass production, feed consumption, etc.), laboratory measurements for nutrient contents, while some data were estimated (nutrient and carbon contents of meat, milk, eggs).

Four scenarios were designed to explore intensification practices in production systems:

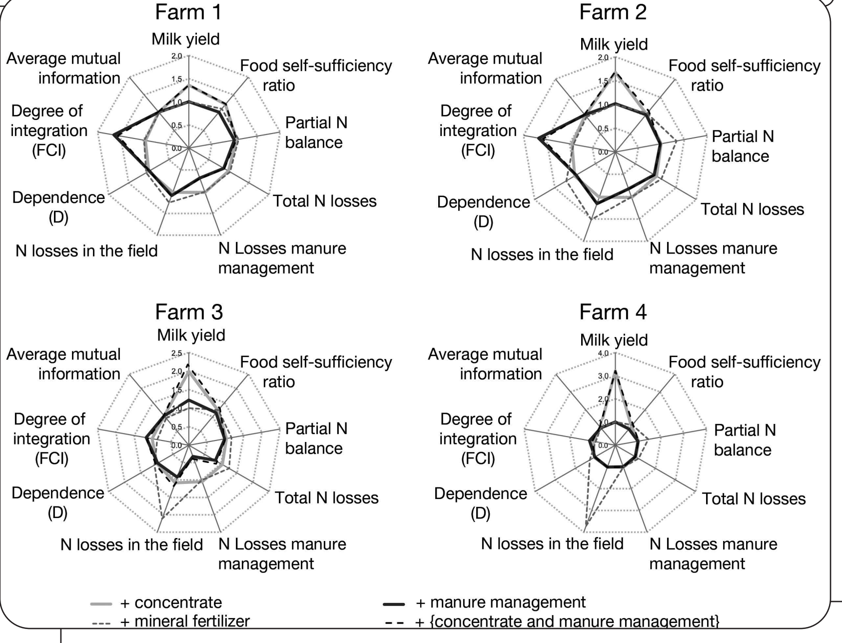
- (S1) nitrogen supply for dairy cows is increased by increasing the intake of concentrate feed,
- (S2) nitrogen supply for rice production is increased by increasing the supply of mineral fertiliser,
- (S3) improving nitrogen conservation during manure storage (covering the manure pile) and during fertiliser application (rapid incorporation into the soil)
- and (S4) the combination of the first and third scenarios.

The indirect effects and feedbacks induced by the scenarios on animal feed, N excreted, N applied in the field, milk and crop yields were taken into account.

The results of the scenarios (Figure 3.12) revealed that manure management practices, such as covering manure piles and rapid incorporation into the soil, could have the best impact on the degree of crop-livestock integration and overall farm energy efficiency (+50% compared to baseline), decreasing total nitrogen losses from the system (–20% compared to baseline). These practices, combined with improved feed quality, resulted in a better economic performance with a significant increase in gross margin for the smallest farms, an increase in milk production (40-300% compared to baseline), household self-sufficiency (30-50% compared to baseline), as well as a decrease in nitrogen losses and an increase in soil nitrogen storage capacity. Large-scale dairy farmers tend to have biomass and nutrient surpluses compared to small-scale farms. Improved internal nutrient management, through better integration of crop and livestock, and more efficient use of available fertilisers, are of interest for farms with low production resource capacity.

These results highlight the need for effective management of organic resources, and specifically the storage and use of manure, in systems that integrate crop and livestock

Figure 3.12. Relative changes in relation to the scenario baseline in terms of productivity, food self-sufficiency, nitrogen balance and losses, as well as network analysis indicators for the four farms in the Highlands of Madagascar (Alvarez *et al.*, 2014).



The four scenarios were: [+ concentrate] increase nitrogen inputs as supplementary feed; [+ mineral fertilisation] increase nitrogen inputs as mineral fertiliser; [+ manure management] improve nitrogen conservation during manure storage and application and [+ (concentrate and manure management)] manage manure and increase feed supplementation. The indicator value observed in the baseline was the reference value (i.e. baseline = 1) in all four radial diagrams.

to compensate for nutrient exports from crops. Therefore, one of the key issues for fertility conservation in crop-livestock systems is to use practices that limit nutrient losses during resource storage.

Territorial integration and landscape efficiency

The work discussed above was based on livestock practices (manure management, feeding, crop-livestock integration) in order to improve the efficiency of the farm. The work in this section still focuses on the agroecological transition in livestock farming, but from a territorial perspective, by attempting to assess the contributions of livestock farming to territorial efficiency.

Landscape efficiency in Amazonia

Orienting the intensification process of livestock systems towards landscape efficiency has become a major challenge for Amazonian territories. This involves adjusting livestock practices and their locations according to land suitability, in order to promote the efficient use of natural resources. Landscapes redesigned in this manner can better respond to agricultural and ecological challenges, such as preserving biodiversity, protecting soils, mitigating climate change and increasing agricultural production.

To promote the transition from the unsustainable use of natural resources inherited from the dynamics of agricultural frontiers, towards the design of efficient landscapes that meet the challenges of sustainability, a comprehensive analysis of land use strategies was first implemented, followed by modelling of landscape changes among ranchers in the municipalities of Paragominas and Redenção, in the state of Pará, as part of a PhD thesis (Plassin *et al.*, 2017).

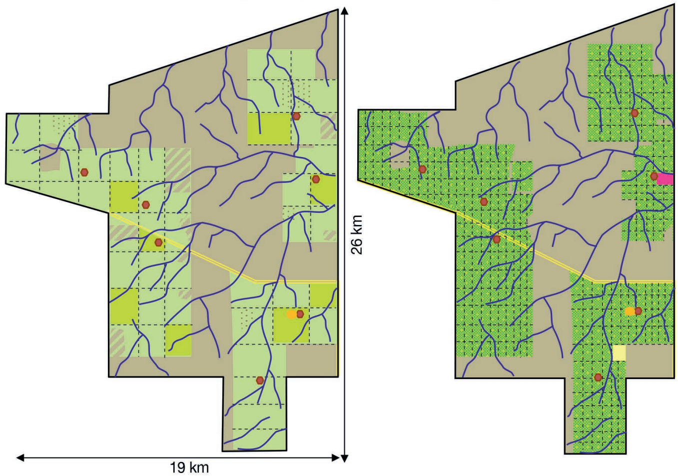
The results show that as ranchers intensify cattle ranching practices, they also change their perceptions of the importance of soil properties, which become preponderant in farming projects. This change in perception of land suitability leads to shifts in land-use dynamics and spatial arrangement. The importance placed on soil properties can be observed regardless of the strategy chosen for improving practices; ranchers take into account soil fertility, texture and bearing capacity, topography, access to water resources, and even the Euclidean distance from the buildings or corral. Fodder intensification on the best soils leads to abandonment elsewhere. The forest-agriculture mosaic also evolves: a new forest matrix occupies areas of little suitability for forage production but is of considerable significance for soils and water protection, forming ecological corridors between the forest patches protected by the Brazilian forest code.

It is this new spatial arrangement of intensified pasture and forest matrix that characterises the efficiency of the landscape (Figure 3.13). Depending on the location and land suitability, the provision of ecosystem services improves, both economically (e.g., more abundant and better quality fodder production, more fertile soils under the pastures)

Figure 3.13. Example of a land-sharing intensification pathways (Plassin *et al.*, 2017).

From 2000: Stop deforestation and restoration of degraded pasture

Farmer project: Cattle intensification through land-sharing and crop-livestock integration



Characteristics in 2000
- 12 700 ha of pasture
- Pastures dominated by a single species (Brachiaria bryzantha)
- 10 000 to 15 000 head of cattle
- Paddock size: 100 ha
- Mechanization
- Natural regeneration of riparian forests
- 57% of farm area in native forest

Characteristics in 2015
- 12 700 ha of pasture
- 15 000 head of cattle
- Paddock size: 20 ha
- Corn production for cattle feed rations
- Rotational grazing

Biophysical attributes
Permanent watercourse

Development
Farm boundaries
Farm building
Corral
Fencing layout
Track

Land use
Forest
Extensive grazing management
Reformed pasture
Ecologically intensive grazing management
Rotational grazing management
Crop (corn)
Fallow

Grasslands are intensified on the basis of agroecological practices (rotational grazing and reduction of paddock size, low chemical inputs, natural tree regeneration). Forest regenerates naturally on areas of low agronomic suitability (e.g. hilly slopes and lowlands) that are abandoned by farmers.

and environmentally (e.g. redesigned habitats that promote biodiversity, improved carbon sequestration and reduction of greenhouse gas emissions, increase of soil and air moisture in the dry season, etc.).

Landscape efficiency indicators can then be calculated using geographic information systems, which will:
- measure spatial match between land suitability and farmers' use of the land, and
- estimate the ecosystem services provided at the farm level.

In both cases, the initial information is derived from satellite imagery and digital elevation models which, in order to be correctly interpreted, are subject to field survey, facilitated by the use of drones and infrared spectrometry. The indicators calculated can then be aggregated at the farm and municipal level, which has a double advantage:
- landscape composition and configuration are approached at a wider scale, which is fundamental for biodiversity and water cycle regulation, for example; and
- local institutions can monitor landscape changes in their jurisdiction, allowing them to design and support specific regulations that are more appropriate than national directives and are often better adapted to farmers conditions (e.g., through the use of municipal land use plans).

Daniel Pinillos' thesis generated a first dataset to quantify ecosystem services in the municipality of Paragominas and to carry out simulations according to local regulations (Pinillos, 2021a). Comprehensive landscape efficiency measures are underway, with the aim of producing a territorial certification label that guarantees the transparency and attractivity of the territory with regards to responsible investors or industries. These principles of landscape efficiency have already inspired the municipality's new "territorial intelligence and development plan", enacted in 2019.

Efficiency and territorial metabolism of contrasted village terroirs in West Africa

In West Africa, agro-sylvo-pastoral systems (ASPS) are traditionally organised on the scale of village territories (called village "terroirs") and are based on the integration of livestock, crops and trees. Through practices that alternate day free-grazing and night corralling, the movement of herds in the village land leads to horizontal transfers of organic matter and nutrients from the rangelands to the cultivated fields. These transfers enable the long-term maintenance of soil fertility and crop production. However, since the 1950s, population growth and the expansion of cultivated land have been to the detriment of rangelands, leading to a decrease in nutrient transfers and challenging the sustainability of traditional ASPSs. As a result, some village communities have reorganised and implemented various strategies at the village level aimed at maintaining animals despite the decline in rangelands.

An original methodology to inventory biomass flows based on household surveys was implemented in the Senegalese groundnut basin to compare these different strategies and to study the territorial metabolism of contrasted village territories. This methodology makes it possible to calculate technical (animal and plant productivity) and environmental efficiency indicators, such as the nitrogen use efficiency. The latter indicator corresponds to the ratio between nitrogen exports (e.g. sale of animals and surplus millet grain) and the village's nitrogen imports (e.g. food and feed purchases for inhabitants and animals respectively). These indicators are used to compare two contrasted village terroirs where rangeland has almost disappeared (Table 3.4). Diohine corresponds to an extensive ASPS similar to the traditional system where a collective fallow is implemented and where the herds remain mobile and extensively fed with local resources (crop residues, grass on fallow land, pruning of fodder trees). The collective fallow corresponds to a set of jointly cultivated plots set aside in the same year to accommodate all the livestock during the growing season. Bary corresponds to a more intensive ASPS where there is no collective fallow and cattle are fattened in the cowshed by largely mobilising feed resources from outside the area in the form of co-products of the Senegalese agro-industry (groundnut and cotton cake, millet and rice bran).

The cattle fattening activity in Bary increases the livestock stocking rate and manure production at village level. The mean annual manure input in Diohine is 0.34 t DM/ha compared to 0.49 t DM/ha in Bary, covering 24% and 31% of the cultivated area in Diohine and Bary respectively. Imported agro-industry by-products to feed animals (3.14 kg kg N/ha in Diohine, 17.6 kg N/ha in Bary) represent an additional input of nitrogen into the land, which is partially redistributed in the agroecosystem through organic manure. These differences in the organisation of nitrogen flows result in differing

Table 3.4. Comparison of two contrasted village terroirs in the Senegalese groundnut basin based on indicators calculated at the territory level for the 2012-2013 agricultural season (Audouin *et al.*, 2015).

Village	Human population density	Livestock stocking rate	Crop productivity (grains)	Crop productivity (crop residues)	Animal productivity	Nitrogen balance (village)	Nitrogen use efficiency
	(hab/km^2)	(TLU/ha)	(kg DM/ha)	(kg DM/ha)	(kg live weight/ha)	(kg N/ha)	(Dmnl)
Diohine	180	0.96	400	2070	25	8.5	0.15
Bary	320	2.31	510	3150	213	24.9	0.64

hab: inhabitants.
TLU: tropical livestock unit.
DM: dry matter.
Dmnl: dimensionless.
All the indicators given in this table are derived from land use mapping, field observations and household surveys. These surveys made it possible to describe the structure of village terroirs and to carry out an inventory of biomass flows between each terroir and its environment and within each village terroir (between households). These biomass flows were then converted into nitrogen flows on the basis of the mean nitrogen content of all biomass, in order to reconstruct the nitrogen metabolism of each terroir.

efficiencies and nitrogen balances among village terroirs. The higher and positive nitrogen balances in Bary underline the greater potential for soil fertility maintenance in this village. The higher N use efficiency in Bary is explained by gains in animal and plant productivities in response to higher N availability for animals and plants. These productivity gains observed in Bary also allow feeding a larger human population (Table 3.4).

These results confirm that nitrogen is a major limiting factor in the productivity of West African agroecosystems, and that increasing nitrogen inputs to villages in the form of animal feeds can simultaneously increase meat production, cereal production and soil fertility. In fact, these external feed resources maintain high livestock stocking rates, intensify ecological processes (including the concentration of fertility through animals) and increase the technical and environmental efficiencies of SASPs (Grillot *et al.*, 2018a). The dependence on external resources raises questions on sustainability; it is acceptable as long as it is limited to the valorisation of by-products of the national agro-industry by animals, since it does not compete with human nutrition. Another sustainable source of nitrogen could be the development of leguminous fodder crops that are atmospheric nitrogen fixers.

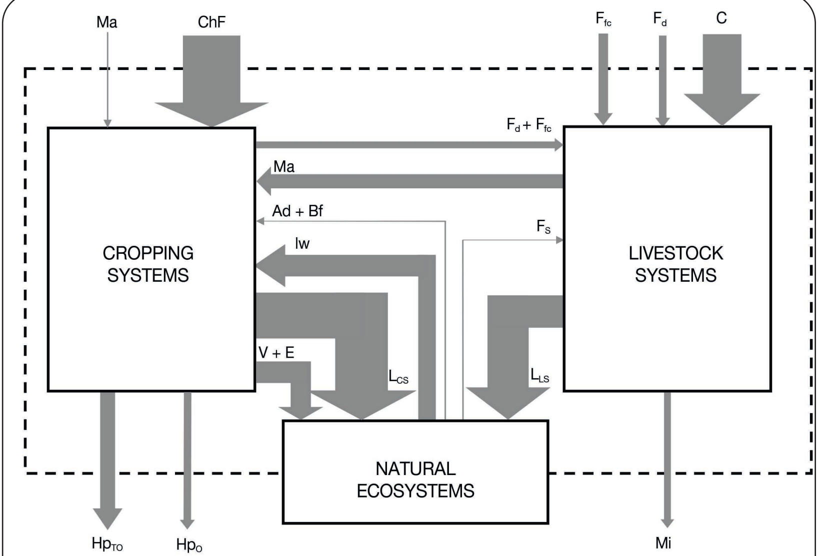
Livestock contribution to the nitrogen metabolism in an Indian village

In the Indian territory of Petlad, in the state of Gujarat, two thirds of the samples taken at village level had nitrate levels in the water that exceeded the drinking water limit of 50 mg/l. In a context of high animal density, an analysis of the territorial metabolism of the village through nitrogen flows was conducted (Aubron *et al.*, 2021) in order to assess the contribution of livestock farming and its interactions with crops to this pollution.

This consisted in conducting nitrogen balances and assessing the efficiency of nitrogen use (nitrogen contained in the products collected/nitrogen supplied) at the plot, herd and farm levels, and then extrapolating these balances to the territory level in order to highlight the nitrogen flows between the various agricultural activities and the components of the ecosystem (Figure 3.14).

It can be seen that, despite a significant potential, crop-livestock integration is limited in Petlad, both at the farm and territorial levels. Nitrogen flows between livestock and crop activities are low compared to nitrogen inputs to each activity, respectively in the form of synthetic fertilisers (65% of nitrogen entering the village) and food concentrates (25% of nitrogen entering). Nitrogen outflows, mainly represented by tobacco (58%), other crop products (22%) and milk (20%) are minor and most of the nitrogen inputs are then lost, to the hydrosphere (more than 600 kg of excess nitrogen per hectare at the crop scale) and the atmosphere. While subsidies for the purchase of nitrogen fertilisers play a major role in this disconnection between crop and livestock production, this study demonstrates that it is also explained by the highly unequal socio-economic structure that prevails in Petlad. Most of the owners with sufficient land (>1 ha) turn to more profitable irrigated crops and tend to abandon livestock. Conversely, the poorest households with limited access to land raise dairy animals to supplement their

Figure 3.14. Representation of nitrogen flows between farming activities and ecosystems in a village in the territory of Petlad (Aubron *et al.*, 2021).



N flows entering the village (*kgN/ha*)
Manure fertilizers (Ma) *(1)*
Mineral fertilizers (ChF) *(715)*
Fodder crops (Ffc) *(75)*
Dry Fodders *(36)*
Concentrate Feeds (C) *(274)*

N flows leaving the village (*kgN/ha*)
Tobacco (Hp_{To}) *(101)*
Other crops products* (Hp_O) *(38)*
Milk* *(Mi, 36)*

Internal N flows (*kgN/ha*)
NH_3 volatilization (V) and N_2O emissions (E) *(158)*
Other N losses from cropping systems (L_{CS}) *(626)*
Irrigation water (Iw) *(126)*
Atmospheric deposition (Ad) and biological fixation (Bf) *(9)*
Manure fertilizers (Ma) *(108)*
N losses from livestock systems (L_{LS}) *(284)*
Spontaneous Fodders (Fs) *(7)*
Dry Fodders (Fd) and Fodder Crops (Ffc) *(36)*

* Milk and other crops products self-consumption inside the village have not been accounted as it was considered as negligible

* Self-consumption of milk and other crop products within the village was considered negligible and not accounted for.

income, but struggle to feed their animals due to lack of access to fodder. While reinforcing the integration of crop and livestock farming in the territory represents a lever for reducing nitrogen surpluses, it does not appear to be easy to mobilise in such a context of social lock-in.

⁂

The examples developed in this section illustrate how ICLS enables progress in agroecological transition, based on the efficiency of associated biological processes: management of animal manure for organic fertilisation, animal feed from co-products, complementarities between farms and activities in a territory. The analysis of efficiencies, and in particular of nitrogen recycling, makes it possible to assess the processes at work in an attempt for improvement. However, in contexts of high population density, recycling is no longer sufficient to meet needs, and external inputs are necessary (mineral fertilisers, concentrated feed) to ensure the balance of the system's functioning: the efficiency of recycling is all the more crucial because it allows these costly inputs to be used in the best possible manner. Moreover, subsidy policies for access to these inputs can have the perverse effect of making recycling less necessary, and consequently slowing down the agroecological transition. All of these considerations were highlighted by the analysis of efficiencies, which confirms the interest of this approach to reasoning the sustainability of livestock farming and its territorial contributions.

This work has revealed the central role that livestock systems can play in the agroecological transition. They are a key link in the recycling of nutrients and the completion of biogeochemical cycles, in addition to supplying foodstuffs, and can be used to develop new forms of agriculture that are both productive and environmentally friendly. However, the examples illustrate the scope for progress in order to make this agroecological transition a success: biological and ecological processes to be explored in order to improve the use of natural resources, recycling of nutrients to increase the efficiency of farms, or complementarity between crop-livestock areas and natural areas for the production of a greater number of goods and services at the territorial level.

Multi-criteria assessment of efficiency to account for the multifunctionality of livestock grazing systems

Jonathan Vayssières, Véronique Alary, Claire Aubron, Christian Corniaux, Guillaume Duteurtre, Alexandre Ickowicz, Xavier Juanes, Samir Messad, Emmanuel Tillard, Abdrahmane Wane, Mathieu Vigne

The two previous subchapters illustrate that the calculation of efficiency provides a means of orienting production towards thrifty resource management and reducing the negative environmental impacts of livestock production systems by calculating indicators such as meat production per quantity of non-renewable energy (NRE) consumed and GHG emissions per litre of milk produced (subchapter Introduction: efficiency, from a simple ratio to an operational analytical framework to support the sustainable development of livestock systems). It can also be used to account for gains in nutrient and energy use efficiency in livestock grazing systems as part of the agroecological transition (sub-chapter *Efficiency to account for the complexity of the contributions of livestock grazing systems to climate change*).

However, the multifunctionality of these livestock systems, notably in relation to the SDG, suggests that other sustainable development (SD) criteria should be taken into account in assessing the contribution of livestock grazing to the SD of territories and in supporting the agroecological transition (FAO, 2018). This is because livestock grazing contributes to a range of non-environmental services and disservices that deserve recognition (Wedderburn *et al.*, 2021; Muller *et al.*, 2021), which vary according to contexts and farming systems and which evolve over time (Vall *et al.*, 2016).

Accordingly, this fourth sub-chapter reviews a selection of research studies that apply a range of quantitative methods and indicators to complement the previously mentioned environmental criteria. Some works go as far as assessing multi-criteria efficiency. The presentation of the various studies is based on an increase in the level of organisation: farm, household, sector and territory, in order to take into account the diversity of issues at these different levels.

Multi-criteria efficiency at farm or household level

The role of livestock in the efficiency and socio-economic viability of family farms in the western Nile Delta in Egypt

The cultivation of desert lands through the extension of irrigation canals is a priority strategy in Egypt to ensure food security in the face of population growth and land fragmentation in the Nile Delta and Valley. However, the development model for these new lands created on the desert raises many debates related to the efficiency and sustainability of agricultural systems in view of the fragility of the soil and the scarcity of water resources (Alary *et al.*, 2018). Alongside large agricultural farms, small areas (1.25 to 2.5 ha) were allocated to a group of beneficiaries, former land tenants or university graduates. The latter have developed mixed crop-livestock farming systems combining market orchards and food and fodder crops with a few head of cattle (1 or 2 cows or buffaloes) and sometimes a herd of sheep and goats not exceeding 10 head.

Based on a survey in 5 localities in the western part of the delta, we constructed a set of indicators related to the notions of technical and economic efficiency in relation to the structure of assets and socio-economic benefits in the production system (Juanes *et al.*, 2020; Alary *et al.*, 2020) (table 3.5).

The results indicate contrasting contributions of livestock to household monetary viability. Among graduates (especially in Tiba), livestock farming helped finance agricultural and family investment during the first years of settlement. Once the orchards were in production, livestock became a source of savings. For the other beneficiaries, livestock plays different roles. In the first areas developed in the 1960s near the delta (Nahda), livestock farming remained a central activity in the system from a technical and economic point of view. In the areas developed in the 1980s, even if the producers in the Bangar area benefit from monetary security thanks to cash crops, the Hamman area has frequent irrigation issues that explain the diversification of livestock activities, in particular with regard to sheep and goats, and a lower economic efficiency per hectare or per family worker. Finally, the highly diversified agricultural systems of the

Table 3.5. Socio-economic characterisation and efficiency indicators of farming systems in newly developed land in the western Nile Delta, Egypt (172 households surveyed in 2014).

Theme	Indicators	Nahda	Bangar	Hamman	Bustan	Tiba	Total
Socio-economic characteristics of the household	Household size (individuals)	11.15	7.70	6.74	9.90	7.40	8.67
	Land area (ha)	3.83	2.26	1.30	1.93	2.66	2.40
	Herd size in livestock units (1 livestock unit = 250 kg live weight)	24.49	12.40	8.23	12.12	6.14	12.69
	Annual net household income (€/year)	17,349	9,698	6,076	10,852	7,460	10,389
	Net income per capita (€/day/household member)	6.0	3.2	2.4	3.4	2.8	3.6
conomic efficiency	Net income per ha (€)	5,482	4,355	3,780	3,371	3,088	3,963
	Income per family member (€)	7,561	4,525	2,667	2,774	3,521	4,123
	Profit (ratio)	0.5	0.3	0.4	0.4	0.5	0.4
	Income from animal products/value of the herd	0.36	0.25	0.45	0.17	1.34	0.51
Technical efficiency of the dairy activity	Feed cost/litre of milk (€)	0.23	0.29	0.16	0.23	0.18	0.22
	Milk yield (litres per animal per year)	1,578	1,190	1,217	1,320	1,535	1,369
	Milk production (€) per ha	1,683	477	620	975	854	926

Bustan region, developed in the 1990s and relatively far from urban centres, mobilises a large part of the available family labour, which explains the lower efficiency per worker. However, thanks to the experience of the farmers, former settlers from the old lands, the technical performance of the livestock is good. More globally, the comparative analysis by area shows that livestock activity contributes significantly to economic efficiency and consequently to the socio-economic viability of rural households in these developed areas in the western delta. However, this contribution needs to be assessed in relation to the contrasting roles of livestock keeping in relation to the availability of natural resources (water and soil), the original settlement (former delta farmers or graduates) and the households link to urban centres. Hence, this analysis shows the need for a multi-criteria and multi-scalar approach to understand and assess the contribution of livestock to the socio-economic viability of a diversity of farms occupying a territory.

Effects of crop-livestock integration gains on the multi-criteria efficiency of dairy cattle farms on the island of Reunion

Dairy cattle farms on the island of Reunion are characteristic of intensive, high-input livestock systems. They consume large amounts of concentrated feed and nutrient-rich mineral fertilisers to fertilise grasslands with a range of associated environmental risks. In a sustainable intensification approach, the aim of this work was to identify practices that would increase the efficiency of nutrient and energy use, while seeking to maintain or even increase the productivity and economic viability of livestock farms.

To achieve this, a simulation model of dairy farming was developed (Vayssières *et al.*, 2011). It simulates the dynamics of biomass stocks and flows and of the nitrogen cycle in dairy cattle farming. The representation and quantification of all biomass flows enables a multi-criteria evaluation of each practice change on the basis of environmental, technical, economic and social efficiency indicators (Table 3.6).

Table 3.6. Consequences of various technical levers defined with the farmers on various efficiency indicators calculated with the Gamede simulation model for a typical dairy farm on the island of Reunion in 2000.

Levers	CLID	Land use efficiency	Feed efficiency	Labour efficiency	Nitrogen efficiency	Energy efficiency
	(SD)	UFL of fodder produced/ha/year)	(litre of milk produced/kg MB)	(gross margin in €/h worked)	(Dmnl)	(Dmnl)
0- baseline, i.e. the system practiced	0.6	4,600	1.16	13.8	0.26	0.35
1- Better use of organic fertilisers produced on the farm	+ 12.5%	+ 10%	0%	– 9%	+ 24%	0%
1- Better use of fodder produced on the farm	+ 3.5%	+ 1%	+ 8%	+ 14%	+ 9%	+ 6%
3- Improved reproductive performances	0%	– 2%	+ 1%	+ 7%	+ 7%	+ 3%
All levers combined (levers 1 to 3)	+ 18%	+ 9%	+ 9%	+ 12%	+ 40%	+ 9%

With the exception of the first line (scenario 0), which is in absolute value, all results are expressed in relative value, i.e. percentage (%) of variation with reference to the values of scenario 0.
CLID: crop-livestock integration degree calculated according to an ecological network analysis indicator based on nutrient flows (Box 3.4).
Dmnl: dimensionless.
UFL: feed unit to produce milk.
GM: gross material of concentrated feed consumed.

The levers highlighted in this study related to a better use of fodder and farmyard manure produced on the farm to replace part of the imported concentrated feed and mineral fertilisers.

The results of the simulations confirm that better use of the resources available and produced on the farm (fodder, organic fertilisers and breeding animals) makes it possible to increase the multi-criteria efficiency of the farm in terms of land use, concentrated feed, labour, nitrogen and energy, while increasing the gross margin of the farms. However, there is a compromise to be found between environmental, technical and economic performance on the one hand and social performance on the other, since, for example, better use of farm resources leads to a higher workload for farmers on the one hand and higher labour efficiency on the other (Vayssières *et al*., 2011).

Multi-criteria assessment of the sustainability of dairy systems in a territory in India

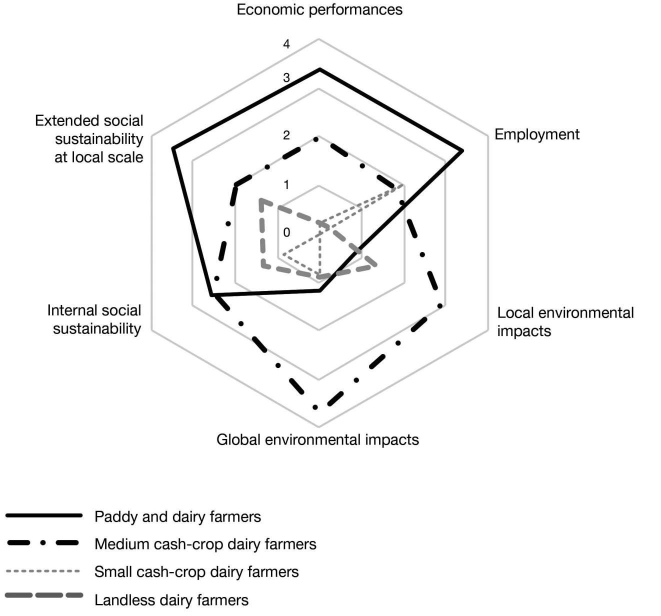
India is currently the world's leading producer of milk due to a development model for the sector supported by structured policies (the "white revolution"). Based on millions of small producers, sometimes landless, owning on average 1 or 2 cow(s) or buffalo(s), dairy farming is often put forward as a major socio-economic development lever for Indian rural societies.

A multi-criteria evaluation method was designed to analyse the internal sustainability of four contrasting dairy systems identified in Vinukonda Township (Andhra Pradesh) and to measure their contribution to the sustainable development of the territory (Marblé, 2019). This method is based on indicators of economic efficiency (e.g., wealth created per animal), employment (e.g., percentage of the active population invested in livestock production), local environmental impacts (e.g., amount of water consumed per litre of milk produced) and global impacts (e.g., GHG emissions per litre of milk produced).

The results were translated into scores and summarized along six main dimensions of sustainability: economic performance, employment, local and global environmental impacts, internal social sustainability and local scope (Figure 3.15). The contribution of dairy farming to the development of Vinukonda Township is based on the diversity of agricultural production systems. Dairy rice farmers are the most economically and socially sustainable system, while medium-sized cash crop farmers (tobacco, cotton, chilli, castor) with dairy farming represent the most environmentally sustainable system. Dairy farmers with limited access to land - small-scale cash crop farmers with dairy farming and landless dairy farmers - score low, notably in terms of social sustainability and economic efficiency, but they contribute to job creation in the area, especially the former.

In order to promote a sustainable and inclusive development of the territory, the promotion of dairy farming must integrate this diversity of systems and guarantee the inclusion of farms with limited land resources. Specifically, this means facilitating their access to

Figure 3.15. Scores obtained for the four dairy systems in Vinukonda Canton (Andhra Pradesh, India) according to six dimensions of sustainability.durabilité.



land and irrigation water so that they can intensify herd management and so increase productivity, wealth creation and income. However, this intensification must not be achieved at the cost of a disconnection between agriculture and livestock farming, as observed in other territories, leading to the consumption of mineral fertilisers and concentrated feeds in large quantities, and hence to negative impacts on the local and global environment (Vigne *et al.*, 2021b; Aubron *et al.*, 2021).

Multi-criteria efficiency at the sector and territory level

Economic efficiency of internationalized beef market value chains in Southern Africa

In most sub-Saharan countries, the meat trade is booming, driven by a combination of growing domestic and regional demand, and even a niche export market such as in Botswana and Eswatini. Meat exports are promoted by these countries for foreign exchange earnings, but also as a means of communicating their ability to produce to often very strict international standards.

The beef value chain in Eswatini, which is studied here, is based on a multitude of small-scale zebu cattle grazing producers. A significant proportion of the beef comes from the contractual transactions of live cattle with Swazi Meat Industries, a beef slaughterhouse and processing plant with exclusive export agreements for quality meat to Europe, mainly Norway. This involvement in international trade chains raises issues of competitiveness, value chain efficiency and domestic market protection.

Their performance was analysed through their contribution to the national and sectoral economy (GDP and agricultural GDP). The domestic resource cost ratio, which measures the comparative advantage of a given value chain over other value chains of products that can use the same type of resource; the nominal protection coefficient, which measures the ratio of the value of products or inputs valued at domestic market prices to those at the border (reference, i.e. without intervention); and the effective protection coefficient, which identifies potential market distortions by analysing the ratio of value added at domestic and global prices are all indicators that can be assimilated to economic efficiency indicators and provide information on the economic dimension of the sustainability of a value chain (Table 3.7).

The total value added created by the beef value chain represents approximately 2% of GDP (1.2% direct contribution and 0.8% indirect contribution) and 32% of agricultural GDP (19% direct contribution and 13% indirect contribution in the form of wage

Table 3.7. Economic performance indicators of the beef value chain in Eswatini (Wane *et al.*, 2018).

Contributions to the national and sectoral economy in 2017					Economic efficiency indicators	
	In billions of euros	Direct contribution	Indirect contribution	Total contribution		
GDP at constant 2011 prices	4.1	1.2%	0.8%	2.0%	Domestic resource cost ratio (DRC)	0.2
GDP at current prices	4.0	1.2%	0.8%	2.1%	Nominal protection coefficient (NPC)	1.2
GDP at constant 2011 prices	0.3	18.8%	12.7%	31.5%	Effective protection ratio (EPR)	0.6
Agricultural GDP at current prices	0.3	19.0%	12.8%	31.8%		

payments, tax payments, etc.). Through taxes, and after factoring in state subsidies (mainly on veterinary drugs provided to smallholders), the beef value chain has a positive impact on public finances. However, it contributes negatively to the balance of trade due to massive imports of meat from South Africa and Mozambique to meet growing local demand. The beef value chain has a comparative advantage in relation to the international market because it efficiently uses its domestic resources (land, capital and labour) to generate added value (CRI<1) by exporting quality meat. It benefits from a certain protection compared to meat imports (CPN>1).

Finally, promoting exports has benefits in terms of improving the balance of payments and bringing products up to sanitary standards to meet a stringent demand in the European market. However, targeting higher quality products for export, while massively producing and importing lower quality products for the domestic market, raises a question of sustainability, notably in a changing world where certain shocks (e.g. health) can challenge existing supply chains.

Assessing the impacts of dairy value chains in Africa: a multi-criteria approach

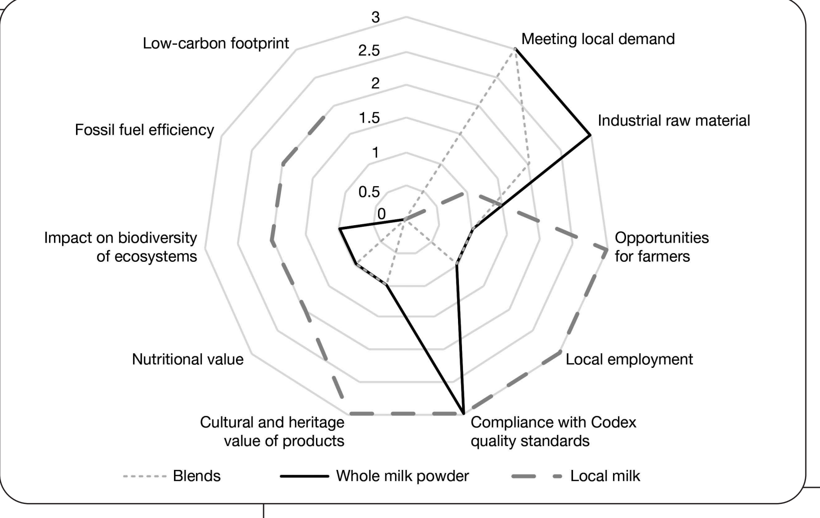
For the Sahelian countries, seriously weakened by various socio-economic crises and climate change, the sale of milk is a means of securing the living conditions of millions of herder and crop farming families. In 2018, these families produced 3.6 million tonnes of milk in West Africa. Most of this milk is consumed or marketed locally and only about 5% is collected by dairies (Corniaux *et al.*, 2014).

The inclusion of these farmers in the dairy value chains is constrained by the difficulties of collecting milk in agropastoral areas. Dairies face the absence of transport infrastructure, the dispersion of herds due to pastoral mobility and low milk yields per cow. Above all, the share of milk powder imports has been increased over the past 10 years by the lowering of West African customs barriers and by the renewed dynamism of exporters in the North. Many European firms have engaged in the export of vegetable fat filled milk powder blends known as "FFMP". These milk powder blends 30% cheaper than powdered milk, mostly use palm oil. They enter the West African market virtually duty free (5%). In 2019, milk powders and FFMP blends accounted for a total of almost 40% of the "dairy product" consumption in West Africa and more than 90% in some capitals (Duteurtre *et al.*, 2020).

Trade policies, which aim to facilitate the entry of cheap imported products to meet demand, are in conflict with dairy sector policies, which aim to promote local production and inclusive value chains that create employment. A multi-criteria approach was conducted to compare the impacts of dairy value chains using differing types of raw materials. This assessment was based on a literature review on the economic, social, nutritional and environmental dimensions of this trade (Duteurtre *et al.*, 2020).

Even if the import of powders has enabled local dairy industries to respond effectively to the growing demand for dairy products, it has nevertheless generated negative socio-economic and environmental impacts. Local milk collection appears to be much more "efficient" than the use of milk powders in terms of job creation in grazing areas in relation to environmental conservation and limiting the risk of consumer deception, because strictly speaking, FFMPs are not dairy products (Figure 3.16).

Figure 3.16. Multi-criteria assessment of dairy value chains in West Africa (Duteurtre *et al.*, 2020).



Scores: 0, somewhat negative; 1, somewhat positive; 2, positive; 3, mostly positive.

This study highlighted that promoting local milk could have significant social, nutritional and environmental impacts. This study needs to be complemented by more in-depth quantitative assessments, especially on the social and environmental dimensions.

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The body of work conducted in North, West and Southern Africa as well as in the Indian Ocean (India and on the island of Reunion) illustrates the extent of the services provided by livestock grazing at several levels of organisation and their contribution to many of the SDGs. These various studies also illustrate how these different services or dis-services can be partly assessed by efficiency indicators. The experience developed in the framework of this study now allows us to provide examples of efficiency indicators to assess the contribution of livestock grazing to the SDGs (Table 3.8).

The implementation of quantitative efficiency indicators for each of the SD dimensions (environmental, technical, social and economic) in practical situations highlights a

Table 3.8. Examples of efficiency indicators to assess the contribution of livestock systems to 10 SDGs.

No	SDG title	Potential usable efficiency indicator (illustrative)
1	No poverty	No. of inhabitants paid by livestock / 1,000 An
2	Zero hunger	kg of milk, meat or protein produced / ha or / household
3	Good health and well-being	ha of (recreational) landscape maintained/ 1,000 An
5	Gender equality	No. of women involved or paid / herd or / household from livestock
6	Access to water	L of water consumed / kg of meat produced or / l of milk produced
7	Access to energy	MJ of NRE consumed / l of milk produced; MJ as biogas produced / 1000 An
8	Decent working conditions and economic growth	No. of jobs generated / 1,000 An
12	Sustainable consumption and production (equity)	kg of product lost along the chain / kg of product at herd level; € returned to the farmer / € paid by the consumer
13	Climate change	kg CO_2 eq emitted / TLU; kg CO_2 eq stored / ha of grassland or rangeland (GHG balance or carbon balance)
15	Terrestrial ecosystems	No. of species present / ha of grassland or rangeland; NH3 emissions / ha or / 1000 An

No: number.
An: animals
TLU: Tropical livestock unit.
NRE: non-renewable energy.
GHG: Greenhouse gas.

set of compromises both in the diversity of livestock systems and in the exploration of ways in which these livestock systems and the corresponding value chains can evolve. These various studies also show that it is not always possible to provide quantitative efficiency indicators for each of the services or dis-services provided by livestock grazing. In other words, efficiency cannot account for all the services and functions of livestock. The quantitative evaluation of the social dimension of SD raises questions. For example, solidarity and equity are social sustainability criteria that cannot be easily assessed in terms of efficiency.

Finally, the calculation of multi-criteria efficiency constitutes a genuine research priority, mobilising sophisticated and complex methods and tools to implement (Boxes 3.5 and 3.6) as well as original conceptual frameworks (Box 3.7). This research work is now eagerly anticipated to inform and identify sustainable development trajectories based on livestock grazing.

Box 3.5. Analysing efficiency frontiers to find the right compromise between productivity gains and environmental impact mitigation in dairy cattle systems.

Emmanuel Tillard, David Berre, Emmanuelle Payet, Philippe Lecomte, Jonathan Vayssières, Stéphane Blancard, Jean-Philippe Boussemart, Hervé Leleu

A study conducted in 2014 (Berre *et al.*, 2014) focused on the identification of a compromise between milk production and its environmental impacts in terms of greenhouse gas (GHG) emissions and nitrogen surplus in high-input dairy farming system on the island of Reunion.

A typical scenario was identified for each of the three "typical" stakeholders in the dairy sector (the farmer, the dairy cooperative and the "environmentalist"). The "farmer" and "cooperative" scenarios seek to maximise milk production without worsening the negative impacts on the environment; the cooperative retains the possibility of increasing the means of production, whereas these are kept constant in the "farmer" scenario. The "environmentalist" scenario is solely aimed at reducing the negative impacts of production on the environment. A fourth scenario, "sustainable intensification", combines maximisation of milk production and minimisation of environmental impacts.

To assess the multi-criteria efficiency of dairy farms, technical and environmental data were collected from 51 farms (Payet, 2010; Vigne, 2007) representing 61% of the island's milk production. An economic optimisation model, called the "efficiency frontier analysis", which is multi-product and multi-factor (i.e. resources and inputs mobilised), was developed to assess the margins of growth in milk production and the simultaneous reductions in GHG emissions and nitrogen surplus.

Milk production is effectively maximised in the "cooperative" scenario and environmental impacts minimised in the "environmentalist" scenario (Table 3.9). Of the four scenarios, the "sustainable intensification" scenario led to the best compromise, with a potential decrease of 238g CO_2 per litre of milk (-13.93% compared to the mean observed level) and a potential increase of +7.72 l of milk produced (+16.45%) for each kilogram of excess nitrogen.

These results are derived from an optimised management of crop-livestock interactions and production processes. However, the environmental impacts of dairy systems on the island of Reunion remain higher than those described in the literature for grassland dairy farming systems (Vigne *et al.*, 2012). These differences could be linked to aspects specific to the island of Reunion context (consumption of imported inputs, availability and quality of fodder) but also to aspects related to herd management (high stocking rate per hectare, grassland management). This confirms that the analysis of efficiency frontiers can shed new light on the comparative analysis of high-input versus grass-based tropical dairy systems.

Box 3.5. Next

Table 3.9. Optimisation of outputs and inputs and environmental efficiency of the different scenarios.

	Relative change in indicators (%)						Indicators in absolute value		
		Consumption of production factors (inputs)			Nitrogen surplus		GHG balance		Bilan GES
Scenarios	Milk production	Herd size	Feed	Labour	GHG balance	Nitrogen surplus	kg N/ha	kg milk/kg N	kg CO_2 eq./l milk
Livestock farmer	+ 5.8%	0%	0%	0%	0%	0%	274	49.6	1.62
Cooperative	+ 14.3%	+ 17.4%	+ 14.6%	+ 20.0%	0%	0%	274	53.6	1.50
Environmentalist	0%	0%	0%	0%	– 13.6%	– 13.7%	236	54.4	1.48
Sustainable intensification	+ 6.6%	+ 7.9%	+ 8.4%	+ 8.6%	– 8.2%	– 8.5%	251	54.7	1.47

Box 3.6. Spatialised multi-criteria evaluation of the environmental and socio-economic impacts of a livestock production chain in several territories.

Jonathan Vayssières, Alexandre Thévenot, Yves Croissant, Emmanuel Tillard

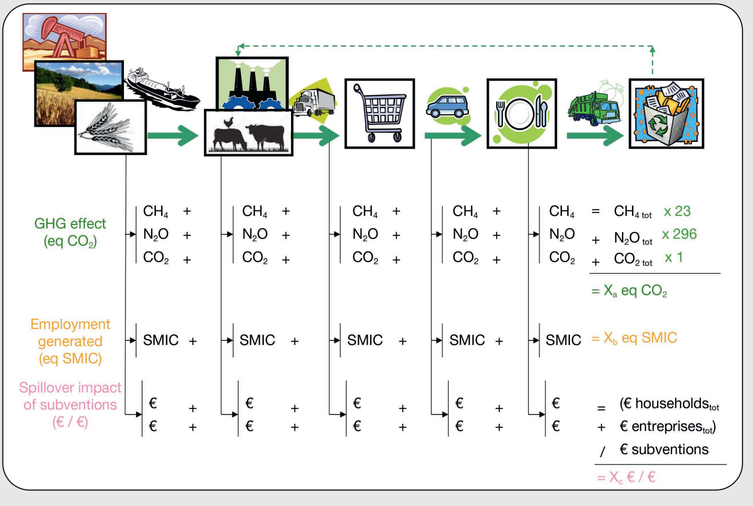
Within the framework of a close partnership with the main stakeholders in the livestock sector in the island of Reunion, we proved that it is possible to integrate two assessment methods based on the same set of inventory data: the environmental life cycle analysis and the effects method (Thévenot, 2014). These two methods, although derived from different scientific disciplines, environmental and economic sciences respectively, make it possible to localise the effect of different scenarios for the evolution of the sector on various categories of environmental (human and ecosystem health, resource depletion) and socio-economic (creation of added value and jobs) indicators along the value chain (figure 3.17). This method is illustrated here on the livestock sectors on the island of Reunion. It should be used again to study value chains built on livestock grazing systems in various regions of the world.

The results for the livestock sectors on the island of Reunion indicate that most of the environmental impacts (around 80%) are externalized from the island's territory, i.e. Europe and South America, due to the high dependence on external resources (fossil energy and raw materials used for livestock feeds). In terms of the socio-economic dimension, most (about 90%) of the job creation is carried

Box 3.6. Next

out on the island through the use of local services (breeding, slaughtering, packaging). Several options for mitigating environmental impacts have been explored with stakeholders in the sector (Thévenot *et al.*, 2013). Improving on-farm feed use efficiency, as defined by the farm-level work described above, was found to be the option with the greatest effect on value chain impacts. Human and ecosystem health and resource conservation would be improved by 2.2, 9.8 and 4.8% respectively; these impact reductions occur both on and off the island. But employment in the industrial network and the island community would also be negatively affected by - 2.2 and - 3.0% respectively. This employment loss occurs mainly on the island; it is primarily the result of a reduction in the quantities of inputs consumed, transported and consequently packaged or produced on the island. These results have been used by the sectors to promote eco-labelling or to lobby the European Commission for support for animal production on the island of Reunion. This study highlights the importance of the compromises between the environmental and socio-economic dimensions and the methodological challenges related to a real integration of evaluation methods from various disciplines at the scale of the entire sector (Vayssières *et al.*, 2019).

Figure 3.17. Multi-criteria assessment of the different environmental, social and economic impacts occurring throughout an animal production chain (Thévenot, 2014).



Box 3.7. Proposal for a conceptual framework for assessing the multifunctionality of livestock grazing systems at the territory level.

Alexandre Ickowicz, Jacques Lasseur, Bernard Hubert, Vincent Blanfort, Mélanie Blanchard, Jean-Daniel Cesaro, Jean-Pierre Müller

Within the framework of an international network on the revalorisation of livestock grazing systems included in the FAO-supported multi-stakeholder platform "Global Agenda for Sustainable Livestock"*, researchers and a group of stakeholders have contributed to the development of an analytical framework and tools aimed at recognising, evaluating and supporting multifunctionality (Hervieu, 2002) and the services provided by livestock grazing systems.

Based on a literature review and participatory workshops involving researchers, livestock organisations, local decision-makers and stakeholders in the sector, we identified the generic and specific impacts and functions associated with livestock grazing. On this basis, we have been able to structure an ontology of the contribution of these grazing livestock systems to sustainable development (Müller *et al.,* 2021) by identifying four dimensions:

- a production dimension,
- an environmental dimension,
- a social dimension,
- a territorial economic development dimension.

The last two dimensions were more specifically developed for the livestock grazing systems, where the socio-economic organisation and cultural traditions, as well as the territorial control of pastures and rangelands are predominant.

Based on this ontology, a conceptual model of the multifunctionality of grassland farming systems was constructed (Figure 3.18) identifying within each of the four dimensions:

- the system elements involved (herd, farmer, industry, plot, atmosphere, soil, etc.),
- the processes/functions describing the impacts,
- and a series of multi-criteria assessment indicators.

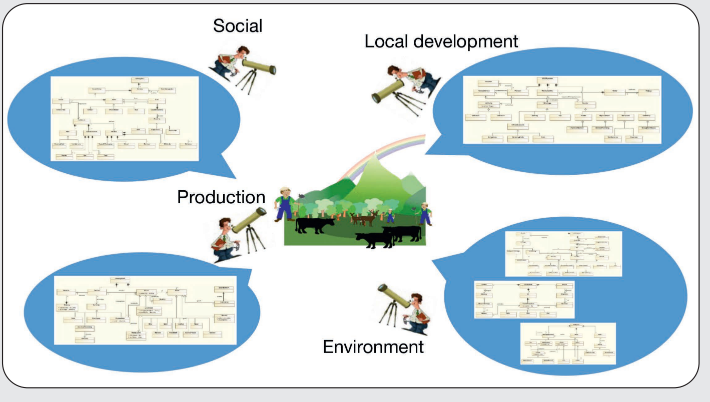
A guide to implementing the method explains the approach, the options for simplification and the possibilities of increasing complexity. It offers an initial series of efficiency indicators (e.g. animal production per hectare used; jobs created per level of production; GHG emissions per hectare used or production level; increase in the mean income per family according to the level of production; number of associations created per level of production; number of infrastructures created within the territory per level of production, etc.). Depending on the scenarios and options chosen, these indicators make it possible to compare and assess the impacts in the four dimensions and to assign them to the SDGs. This approach and these tools have been tested, validated and enriched on 6 pilot sites around the world in various contexts (Argentina, Brazil, France, Mongolia, Senegal, Vietnam;

Box 3.7. Next

Wedderburn *et al.*, 2021; Ickowicz *et al.*, 2022). These have led to the identification of several areas of application at a territorial level: decision-making assistance for the development of livestock or sector models, for the choice of activity priorities in favour of territorial development, assistance in the construction of multidisciplinary research teams, etc. This conceptual model has also led to the development of simulation models. Through several scenarios, either in the form of educational "toy models" or in the form of specific models applied to the field context, their use is intended to facilitate discussion between territorial stakeholders and the identification of compromises to be managed between several options, functions, indicators and impacts.

This approach to the multifunctionality of grazing systems should therefore make it possible to develop a multi-criteria approach based on a systemic analysis of the role of livestock grazing systems within territories that takes into account the interactions and trade-offs between dimensions and indicators. It calls for the mobilisation of a range of disciplines and stakeholders in order to account for the different points of view and interests and to collectively provide options for the sustainable development of their territory.

Figure 3.18. Illustration of the conceptual model of the multifunctionality of livestock grazing systems.



* www.livestockdialogue.org.

Conclusion and perspectives

René Poccard-Chapuis, Vincent Blanfort, Fabien Stark, Jonathan Vayssières, Mathieu Vigne

The notion of efficiency and the applications of this concept in the scientific sphere have evolved over time in line with the current societal issues. Originating with productivism, within which it constitutes a technical-economic indicator among others to evaluate performance, efficiency took on a new meaning when tools were sought to economise resources, in particular energy resources: initially for their cost, and later for their scarcity, and more recently for their impact on global warming and the environment. Far from being a 'catch-all' concept, efficiency, as a tool for analysis and reflection, can therefore be adapted to a variety of contexts and contribute to addressing numerous issues, as illustrated by the preceding examples.

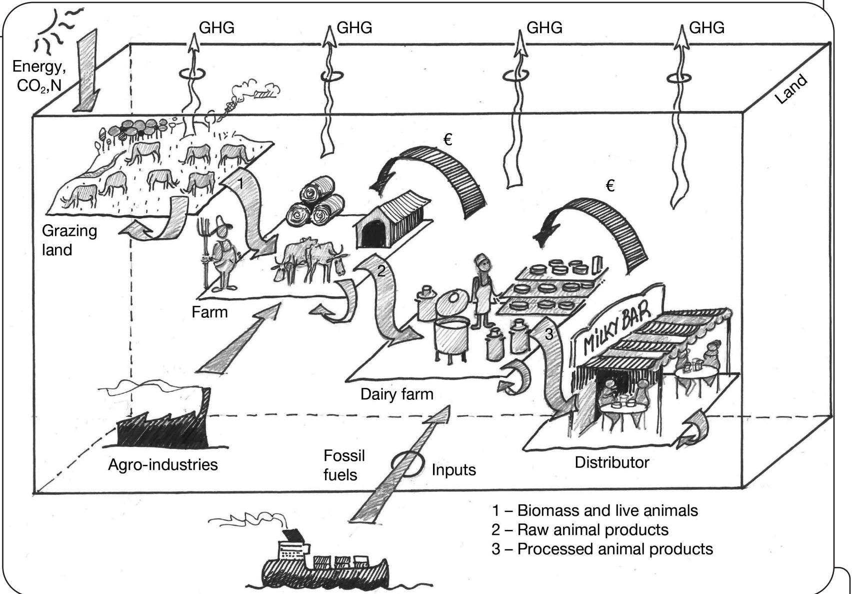
This capacity of the notion of efficiency to produce quantitative indicators relevant to the issues of each era is invaluable today in livestock farming. In the face of the numerous criticisms and opportunities in the world of modern animal husbandry, what does efficiency have to offer us?

In terms of method

The absence or scarcity of established scientific references, which would allow an evaluation of the efficiency of tropical livestock systems for grazing, is very clear from the various examples. As a result, the insights and analyses are based on partial assessments, supplemented by a transfer to the South of data and concepts developed on farms and territories in the North. The limits of this approach are clear, in view of the differences at all levels: the operating methods of grass-fed livestock systems are very different in the tropics. The methodological challenge is therefore crucial in producing the scientific references that are missing.

This chapter describes a wide range of methods used to analyse efficiencies in various tropical livestock areas. It clearly illustrates the adaptability of the concept of efficiency, which is essential for analysing a sector as diverse as livestock production. The authors have given us an overview of the diversity of applications for this concept, in highly contrasting contexts. A wide range of criteria can be integrated into the calculation of livestock efficiency, whether in terms of resources mobilised, energy, nutrients, land, labour, etc., or in terms of services or dis-services generated: food, protein, GHG emissions, employment, added value, etc. These are all possible views, each of which can make sense in terms of the specificity of one issue or another. There is also diversity in the spatial dimension or scale of analysis: efficiency can be measured from forage plots to territories or livestock sectors and even beyond. Finally, there is a diversity of dimensions, as efficiency applies as much to the technical or biological and environmental fields as to the social and economic fields (Figure 3.19). All these levers offer possibilities for fine-tuning the choice of criteria, according to the problem at hand.

Figure 3.19. From the plot to the territory, the overlapping of multi-criteria and multi-level efficiencies calculated from different types of flows: materials, greenhouse gases (GHG) and money (€). Illustration: É. Vall.



The analysis of efficiencies can relate to various types of flows: material, income, energy or greenhouse gas emissions. It can also focus on specific compartments, such as the grazed plot with its herd, the farm, the sector or the territory. Each of these approaches reflects complementary aspects and perspectives, which enriches the assessment and allows for relevant comparisons between farms, regions or livestock systems, including at the global scale.

Another virtue of the concept of efficiency is to represent complexity as effectively as possible on the basis of a simple criterion. The various methodological boxes in this chapter highlight the complexity of the calculation methods behind the simple and synthetic efficiency indicators. In addition to these indicators, the extent to which efficiency makes it possible to develop systemic reasoning beyond the single criterion being assessed, is demonstrated. Based on an equation and its analytical reasoning, the authors mobilise, and accordingly question, all the factors and mechanisms which, by interacting, govern the targeted criterion in each case study. This systemic view is particularly fruitful when it comes to shedding light on the functioning of activities as complex as livestock farming, notably livestock grazing. In this way, nitrogen efficiency does not simply involve a digestibility or metabolism equation, but requires consideration of the multiple biomasses involved, classifying the transformation processes to which they are subjected throughout the biomass recycling loop. Ultimately, this leads to consideration of integration of agricultural and livestock activities, the flow between grazed, cultivated or fertilised areas and the labour force involved. The depth of the long term can also be considered if necessary, as in the Brazilian Amazon: an analysis of the efficiency of landscapes in this livestock-raising region means reconstructing how, over time, the occupation of space was based first on criteria of land appropriation, then on environmental regulations and today on the agronomic aptitude of the soil for fodder production. It is this accumulation of traditions that forms the landscape in which farmers and their animals evolve, and which efficiency analysis helps to decode.

There is no doubt that these two methodological characteristics, based on plasticity and systemics, make efficiency a valuable concept for analysing contemporary livestock farming and thereby understanding the possible forms of livestock farming of the future. This is especially true since it is possible to combine several criteria, or levels, in integrative assessments. Multicriteria and multilevel analyses are suitable for understanding a third fundamental characteristic of grass-farming: its multifunctionality. This is abundantly illustrated here, from India to the Amazon, via the Nile delta, the plateaus of Madagascar, the Cévennes hills and transhumance in the Provence. In no place is grass-farming limited to the production of meat, milk, or even leather or fibre. According to the environments and societies in which they are embedded, these livestock systems fulfil other functions, such as land control, asset accumulation, savings, social status or prestige, and the production of multiple ecosystem services or dis-services. The examples in the sub-chapter The pursuit of efficiency to support the agroecological transition in livestock systems reveals how multi-criteria analysis is essential to account for this multifunctionality and how efficiency can reflect several of these criteria. Our work on multifunctionality also highlights the limits of efficiency analysis, even when it is multi-criteria, which does not always produce the relevant indicators, for example in the social dimension. This is one of our fields of research, to improve the consistency of the methods for calculating these multiple indicators.

In terms of communication

Livestock farming is at the core of numerous controversies, where information is often partial and influenced by a biased message and where scientific impartiality is sorely lacking. It is regularly criticised, notably in the wake of health or environmental emergencies. In addition, new controversies are emerging and public opinion is raising questions about the nutritional risks associated with meat consumption, the production of artificial meat and the rights and well-being of farm animals. Positive views are also expressed on grass-fed farming, praising the interest of shorter circuits, the contribution of farmers to the maintenance of landscapes, the quality of taste or the cultural values attached to livestock products and territories. In this often passionate, even conflictual context, lobbies are formed and appeals are drafted. Communication becomes an issue, a terrain where stakeholders clash, and where simplification is a strategy or even a weapon, leading to the risk of misinformation.

Efficiency also has advantages in this area of communication: it simplifies without being overly simplistic, which makes it valuable for enriching societal debates on livestock production. Comparing resources to outcomes, or undesirable products to intended products, are simple enough intellectual exercises to be well understood or applied, and meaningful enough to make people think beyond preconceived notions or activist slogans. This chapter provides numerous illustrations which, if transposed into public debate, could improve the formation of opinions, precisely because they are based on these principles of simplicity, integration of complexity, relevance to the diversity of issues and objectivity of understanding. In this way, the efficiencies approach can be a genuine gateway for communication between science and society.

In the field of consultancy and policy guidance

Livestock farming faces numerous transitions around the world. This is why farmers and institutions require objective criteria to make their decisions. Given the complexity of the processes, efficiency measures can be used to weigh up the criteria and identify the most acceptable compromises, especially in terms of livestock practices, but also in terms of sector-based or territorial policies. Studies on the agroecological transition are highly illustrative on this subject. Although they were conducted in different contexts, they all show how measuring efficiency enables researchers to make relevant diagnoses and identify which practices or measures make sense, or would make sense, in terms of local conditions.

However, these studies also indicate that these perspectives are rarely, if ever, mobilised beyond the circle of researchers and academics. Sectoral policies do not promote efficiency in the Senegalese dairy sector or in the internationalised meat sectors of Southern Africa. Crop-livestock integration in Gujarat, India, is limited by farmers easy access to nitrogen fertiliser. In Guadeloupe, intensification and specialisation have been preferred to crop-livestock integration, which is currently holding back the agroecological transition. In other words, although the interest in efficiency approaches is obvious, their appropriation by political stakeholders is limited. The challenge is to go beyond the stage of academic studies so that these indicators are integrated into the standards used by development stakeholders.

Sustainable finance, or green finance, could play the role of catalyst for transitions. It calls for standardised efficiency measures in standard protocols and the establishment of this approach based on carbon footprints and ecosystem services. But these guidelines are still at the trial stage. Similarly, in the public sector, the transfer of competences to municipalities is a major trend in public administrations around the world, directly impacting livestock catchments. They offer the possibility for local institutions to choose their efficiency criteria to build innovative regulations at their level, such as territorial certification. In addition, value chain stakeholders are also attentive to and potentially interested in the mobilisation of these indicators with a view to moving agricultural sectors towards more socio- and eco-responsible forms of production, in line with product certification procedures.

Finally, democratisation of the use of efficiency measures seems to be a priority in order to better communicate on the diversity of livestock systems and their contribution to sustainable development objectives, as well as to better advise livestock owners and decision makers. While the evaluation methods are rich and well adapted by the scientific sphere, it is the sphere of development and decision-makers that must now be targeted.