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

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

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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*

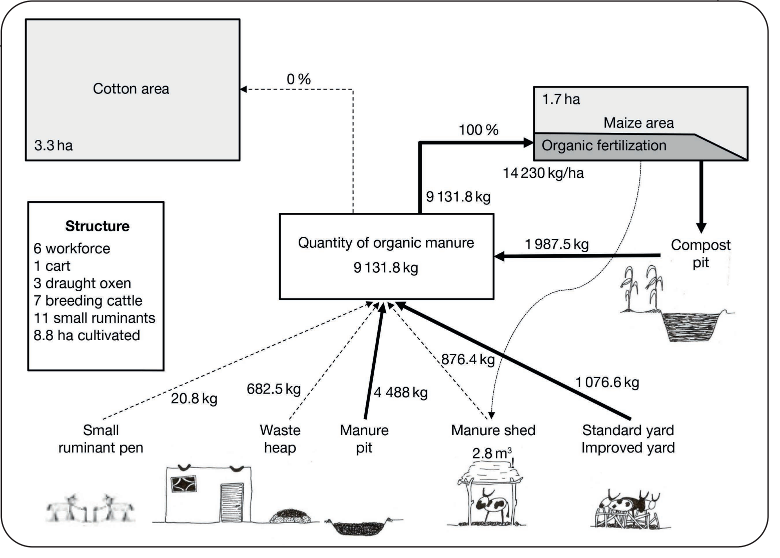
Work carried out in the West African savannahs (Mali and Burkina Faso) focused on characterising organic manure production and management practices, which are used to recycle biomass to fertilise soils, a recurrent problem in all the so-called cotton-growing (sub-humid) areas of the region (Blanchard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

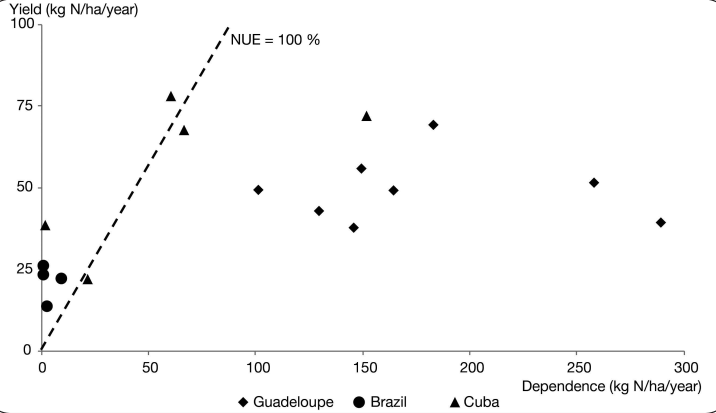
In order to assess the contribution of nutrient cycling to the so-called agroecological performance of mixed crop-livestock systems, a comparative analysis of crop-livestock integration practices between farms in three Latin-Caribbean territories (Guadeloupe, Brazilian Amazon and Cuba) was carried out 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*

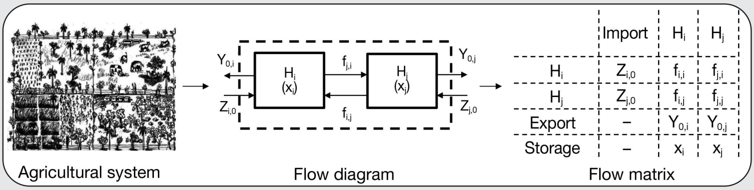
Mixed crop-livestock systems in the West African savannah (Mali and Burkina Faso) tend to integrate livestock and crop activities. While much work has been conducted on the capacity of ICLS to improve the resilience and productivity of these systems, little has been undertaken to analyse its contribution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

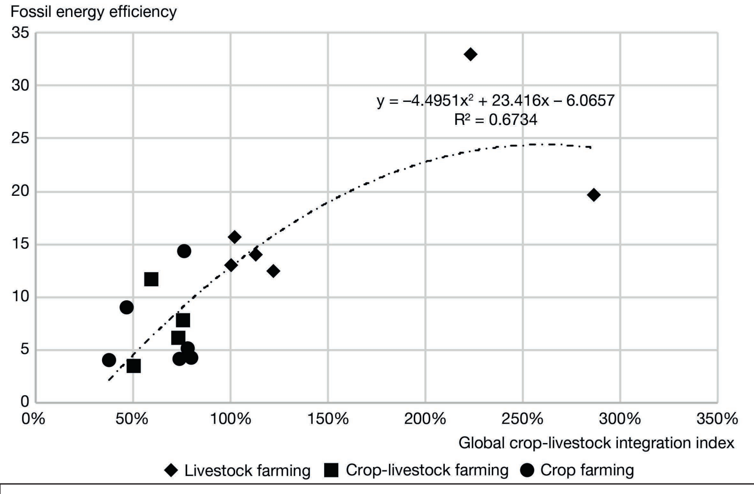
**Table 3.3. Crop-livestock integration indicators and performance indicators.**

| 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 $\Phi$ / 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).

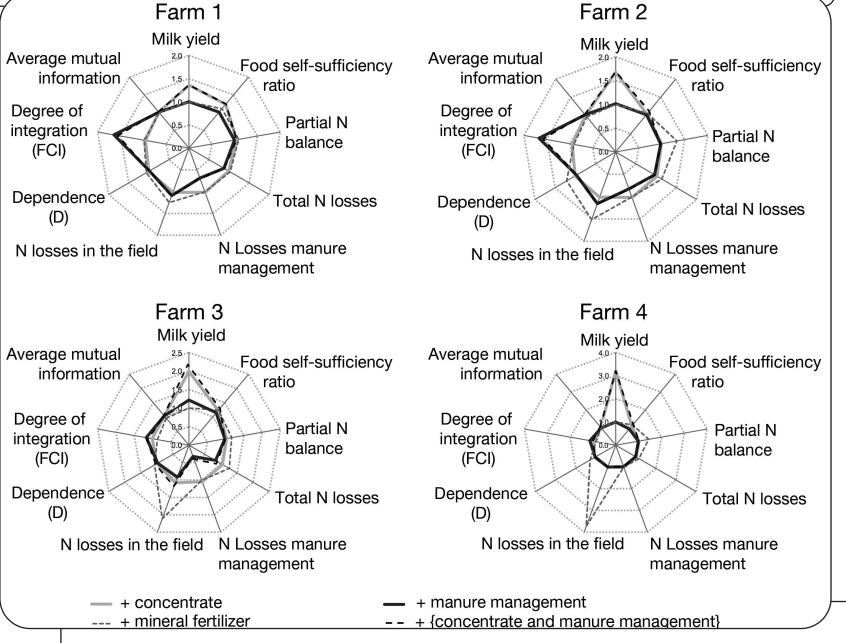
Four scenarios were designed to explore intensification practices in production systems:
• (S1) nitrogen supply for dairy cows is increased by increasing the intake of concentrate feed,
• (S2) nitrogen supply for rice production is increased by increasing the supply of mineral fertiliser,
• (S3) improving 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*

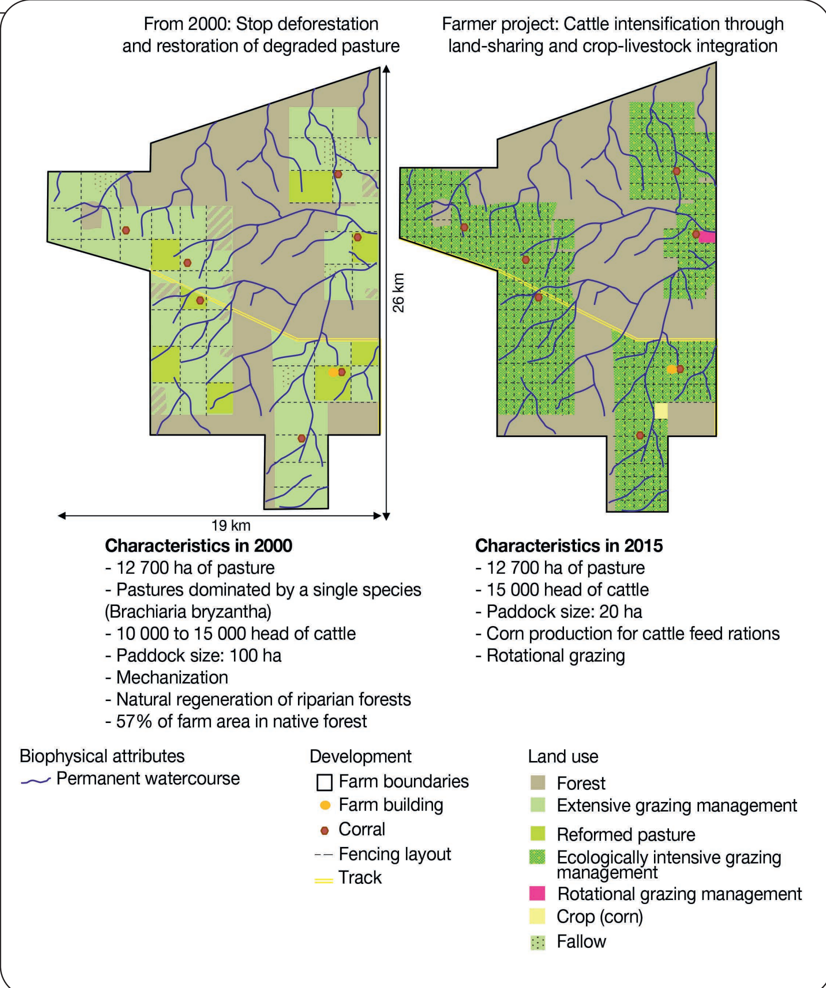
Orienting the intensification process of livestock systems towards landscape efficiency has become a major challenge for Amazonian territories. This involves adjusting livestock practices and their locations according to land suitability, in order to promote the efficient use of natural resources. Landscapes 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).**




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 low-lands) 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.

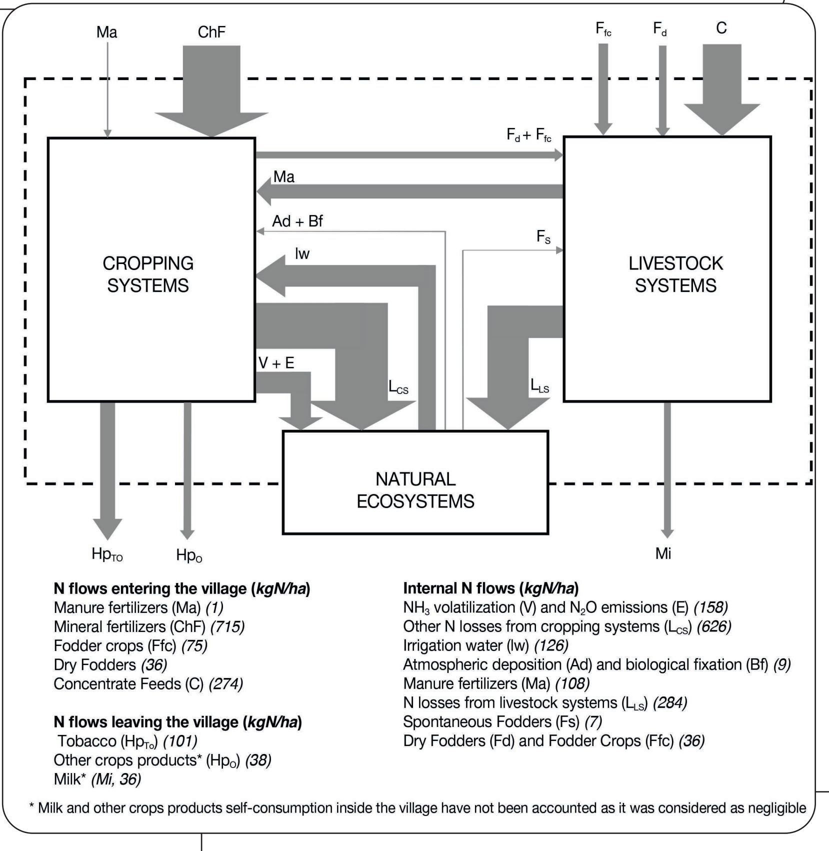
### *Livestock contribution to the nitrogen metabolism in an Indian village*

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).**




* 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.

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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

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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