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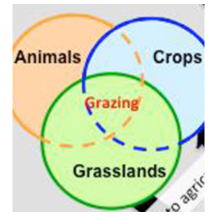
An analytical framework for structuring analysis and design of sustainable ruminant livestock systems



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Implications

- Land use of livestock systems at different spatial and temporal scales is a particular concern among environmental and food-security issues.
- We present an analytical framework that conceptualizes livestock systems as social (economic and social organizations/institutions) and ecological (grasslands, crops, and animals) systems. The framework highlights relations between social dynamics, land use, environmental impacts, and ecosystem services.
- This framework distinguishes two archetypes of ecological modernization in livestock systems: efficiency based and biodiversity based. Each includes specific land use and economic reasoning. The first optimizes input use and genetics without a change in land cover. The second increases and manages plant and animal diversity at the farm or landscape level to enhance the provision of ecosystem services.
- These archetypes are broken down into six scenarios of sustainable livestock systems. We illustrate several scenarios by analyzing two types of dairy farms in Brittany (northwestern France) and a project of organic farmers aiming to develop interactions between specialized farms in southwestern France. Examples show the potential of the biodiversity-based pathway to enhance ecosystem services and reduce input use at local or collective levels.
- Our analytical framework can be used as an intermediary object to support stakeholders in structured design and assessment processes to identify main issues of current livestock systems and the characteristics of possible sustainable pathways.

Key words: biodiversity; economy of scope; economy of scale; ecosystem services; land use; social system

Introduction

As observed at the global level (Herrero et al., 2013), ruminant livestock systems in Europe pollute the air (CH_4, N_2O, and CO_2) and water (NO_3) and erode biodiversity, but they also produce valuable manure for agricultural land. They can be a source of diet-related diseases but are also a source of critically important protein and micronutrients in the human diet. There is growing recognition that improving the environmental performance of livestock systems and establishing sustainable levels of animal-sourced food consumption are essential for the sustainability of the global food system (Bellarby et al., 2013).

Such positive and negative impacts depend on land use and location characteristics (e.g., lowland, highland), both of which vary greatly within and between regions depending on farm structures (specialized or mixed crop–livestock systems) and feeding strategies (grass-based regimes or stocked-forage regimes, either produced on farms or bought to supply chain). Links between livestock and land, from farm to local regional levels, depend on feeding regimes but also indirectly on how stocked manures are managed on the farm or beyond the farm.

In intensive lowland and intermediate zones of Europe, increasing the size and specialization of livestock farms to achieve an economy of scale is a strong trend. This trend is often associated with a reduction in grazing and grassland and a decrease in mixed crop–livestock farms, both often leading to an increase in environmental impacts. Farm size also increases in zones with high nature value, where the main challenge is maintaining current environmentally-friendly systems under difficult economic conditions. These two trends continue, despite regional, national, and European public policies.

The impacts of livestock are partly due to farm and regional specialization, which goes along with the use of industrial feed inputs or systematic antibiotics (FAO, 2006). Environmental problems are not due so much to the animals themselves but rather to how they are integrated into agroecosystems and food systems (Gliessman, 2006). Two key issues regarding food security are: (i) the quality of animal products (e.g., fatty-acid composition), which depends largely on livestock feeding regime (e.g., grassfed vs. maize–soybean fed) and so on land use, and (ii) the competition between livestock and humans for grain consumption.

Assessing the sustainability of current livestock systems or designing sustainable alternatives requires analyzing corresponding land use, feeding systems, and food systems. Current frameworks that characterize ruminant livestock sustainability are limited, especially in considering land-use effects and their multi-level and multi-domain (ecological, economic, social, and institutional) intrinsic characteristics (Duru and Therond, 2014). Analyzing the sustainability of agricultural systems by considering their capacity to deliver ecosystem services (**ES**) (Zhang et al., 2007) would be a good way to overcome limitations of static assessment procedures. Certain regulating services (e.g., soil fertility and biological regulations) increase the potential of autonomous production (i.e., without exogenous inputs) of the agricultural

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ecosystem and enable farmers to depend less on marketed inputs (e.g., mineral fertilizers and pesticides) and irrigation water. Agroecosystems provide society with regulating and cultural services that are mostly not directly marketed (e.g., C sequestration and aesthetic landscape). Snapshot sustainability assessment based on the classic "triple-bottom line" most often implicitly considers, in a "weak sustainability" approach, that human and natural capital are substitutes. In contrast, an ES-based approach analyzes how socio–economic activities depend on nature at different levels (Wu, 2013).

We present an integrated analytical framework that encompasses the complexity of livestock systems and enables relationships among land use, environmental impacts, and ES in livestock systems to be identified. The framework conceptualizes livestock systems as social-ecological systems to represent how the social system determines land use and ES. It also highlights the two main pathways of ecological modernization of livestock systems: managing input efficiency to decrease negative environmental impacts or managing biodiversity to increase ES. Using this analytical framework, we present several possible scenarios of these two forms of ecological modernization and use case studies to illustrate them and discuss their sustainability.

Ewes grazing in a multi-functional landscape: Southwest of France (source: J. P. Choisi Inra).

An Analytical Framework to Characterize Current and Future Livestock Systems at Different Levels

The agroecological system

In livestock farms, potential ruminant's feed resources are perennial and temporary grasslands and various forage crops, most often maize for silage and sometimes by-products of cash crops such as maize stubbles. To represent the diverse land uses at farm and regional levels, our analytical framework distinguishes two land use "spheres" and the animal sphere to represent how they spatially and temporally interact to varying degrees (Moraine et al., 2014) (Fig. 1). The Crops and Grasslands spheres correspond to two primary agricultural production areas that are composed of a range of species or species mixtures with specific functions. Small and large woody species are possibly included in these spheres. Their presence varies and includes lone trees, hedgerows, agroforestry, and moors. The Grasslands sphere includes cut or grazed permanent grasslands (overlap with the Animals sphere) and grasslands in rotation that are mowed (overlap with the Crops sphere) or mowed/grazed (overlap with the Crops and Animals spheres). Permanent grasslands, and to a lesser extent temporary grasslands, are a key land use for delivering ecosystem services at the watershed (e.g., water-quality regulation) and global levels (e.g., climate regulation through C sequestra-

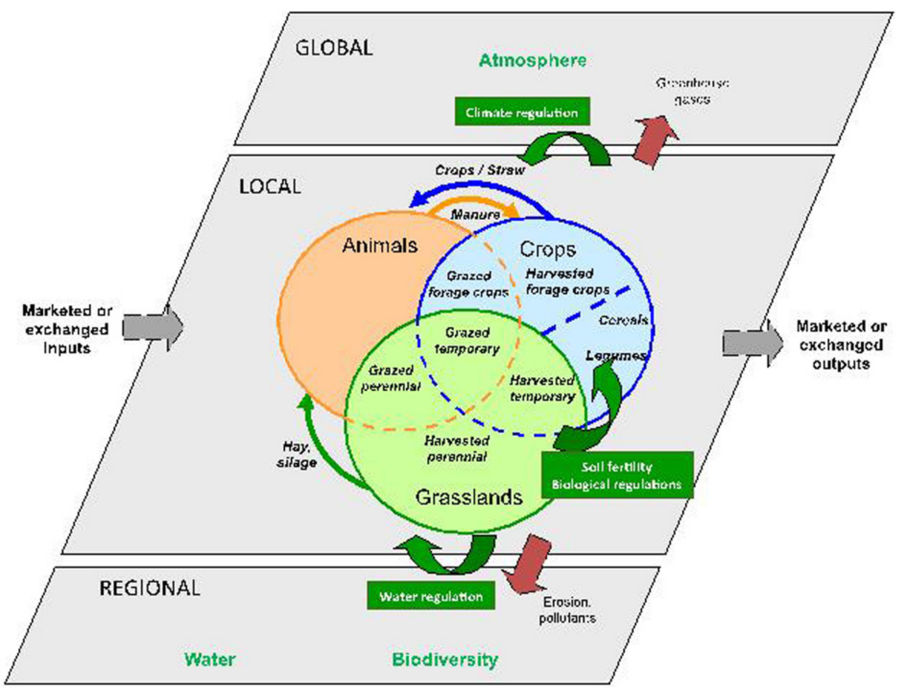


Figure 1. Spatiotemporal interactions among crop, Grassland, and animal "spheres;" key material flows; environmental impacts; and ecosystem services of livestock systems from local to regional and global levels. For illustration, the three spheres and overlapping areas have similar dimensions. By varying their sizes and degrees of overlap, it is possible to represent the structure of a wide range of livestock systems: grassland based (no crops), forage crop based (no grasslands), and crop–livestock systems in which certain crops are cash crops and others are used for animal feed.

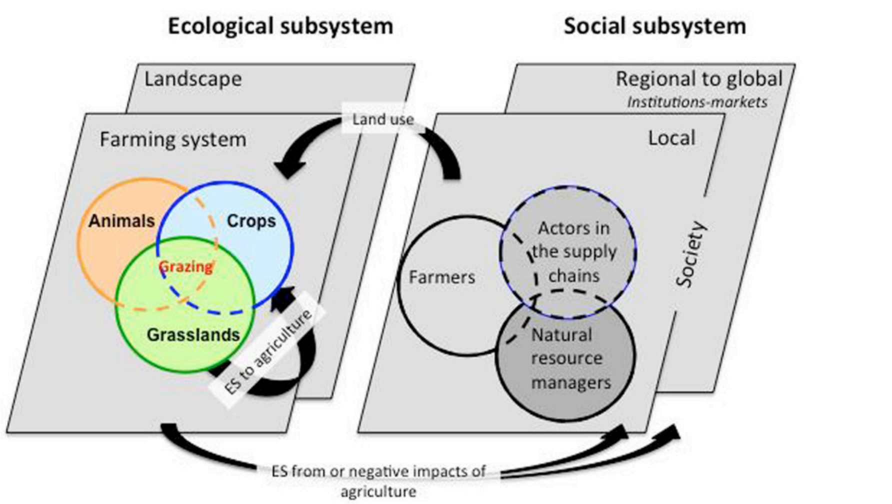


Figure 2. Interactions within and between social and ecological subsystems in a livestock system and the nested hierarchy in which they are embedded. Interactions between agricultural stakeholders determine land-use practices in livestock systems and, in turn, the ecosystem services (ES) delivered to civil society or to the farmers themselves. Curved arrows represent key relationships between ecological and social components. In the ecosystem, they represent services to farmers.

Figure 3. Workshop participants and example of visual aids used for participatory design of livestock systems.

tion). When in rotation with crops, grasslands also play a key role in coupling nutrient cycles and in enhancing biological regulations at the local level (Soussana and Lemaire, 2014). Grassland-based legumes play a particular key role because they improve soil physical, chemical, and biological fertility within cropping systems and contribute to protein autonomy in livestock systems. The distinction between cash crops and forage crops allows distinguishing management practices, such as dual-purpose crops, when crop allocation is modified by a tactical switch from one use to the other. The destination of cash crops does not exclude the use of by-products such as straw for feeding livestock or crop-residue grazing. The Animals sphere is composed of groups of animals, each of whose species, breed, or performance level is relatively homogenous. The characteristics of each animal group, or combination of them, determine the type and quality of resources it consumes as well as the quality of its wastes. This determines how the two previous spheres are used.

When represented graphically (Fig. 1), overlapping sphere areas represent direct spatial interactions, either simultaneous (e.g., grasslands grazed by animals) or over time in the form of a sequence (e.g., grasslands in rotation with crops). Interactions between the three spheres strongly determine the level of emissions into the atmosphere and water and of ES delivery to agriculture (Fig. 1, center box) and society (Fig. 1, upper and lower boxes) (Duru et al., 2015a). Crucial features of land cover/use for delivering ES include:

- spatial pattern, crop–grassland sequences and grassland management (Franzluebbers et al., 2014; Soussana and Lemaire, 2014)
- proportion of crop rotations composed of legumes or mixed (or multiple) crops such as cereal–legume mixtures (Gaba et al., 2014)
- botanical composition of grasslands, in particular the proportion of legumes (Lemaire et al., 2014)
- grazed areas, including permanent grasslands, temporary grasslands in rotation, intercrops, or crop residues (Soussana and Lemaire, 2014; Wardle et al., 2004)
- area and intensity of animal manure application on field crops (Soussana and Lemaire, 2014)

Land cover and use influence biodiversity levels and trophic chains above the soil (e.g., birds, insects) (Power, 2010) and within the soil (e.g., earthworms, bacteria, and fungi) (Koohafkan et al., 2012), which determines soil fertility, biological regulations, and control of weeds, pests, diseases, and pollination (Ratnadass et al., 2012). Ecosystem service-like provisioning services also depend on these variables (e.g., climate regulation via C sequestration, water filtration and flow regulation, erosion control, genetic resources, and cultural services). Therefore, strong interactions occur between services and agriculture via the ecological component of agricultural systems (Garbach, 2014).

Interactions between the agroecological and social systems

Crop–Grassland–Animal interactions within livestock systems depend on the local and regional social system in which farmers are embedded. Actors and institutions in the supply chain and natural resource managers are key components of this social system. In this social system, formal and informal agreements determine the behavior of stakeholders, including farmers (Fig. 2). At the farm level, interactions across ecological, economic, and social domains determine agricultural practices. Interactions also occur across time scales at the field level (e.g., cumulative effect of soil management techniques on soil fertility) and at higher levels (e.g., nitrogen cascade at landscape level) (Duru et al., 2015a).

Livestock systems, as other agricultural systems, are embedded in a complex hierarchical system. Interactions between subsystems of the nested hierarchical system occur within levels (e.g., between field and between farms) and between levels and domains via biophysical and socio–economic processes (Duru and Therond, 2014). For example, the status of the landscape (e.g., water and biodiversity) depends on the aggregated effects of land use, which in turn, affects biophysical dynamics at the field level (water availability and biological regulations) and possibly environmental policies at national or regional levels. Local markets and institutions, supply chains (e.g., labeled products), and farming systems have varying degrees of interdependence.

Addressing sustainability issues in current livestock systems requires considering the diversity of stakeholders' views and interests through a structured participatory design-and-assessment process (Duru et al., 2015b). The latter is characterized by co-specification of the problem and objectives (Fig. 3). The analytical framework presented above was used successfully as an intermediary object to support stakeholders in multiple European case studies to identify main issues of current livestock systems and to design alternative systems (Moraine et al., 2014).

Two main pathways of livestock ecological modernization

Two main ecological modernization pathways, greatly differing in their underlying paradigms, are currently identified to address the considerable environmental and socio–economic challenges of agricultural systems (Horlings and Marsden, 2011). For the more common one, called an efficiency/substitution-based modernization, sustainability is pursued by reducing negative environmental impacts through increasing input-use efficiency and substituting chemical inputs with biological ones supposedly less harmful to nature. This modernization pathway, a continuation of productivist agriculture, pursues its rationale of economy of scale to ensure competitiveness in the regional and global market and in the bioeconomy. It promotes specialization and simplification of farming systems that are poorly connected to local issues and depend little on local farmer interactions. The other ecological modernization pathway, called a biodiversity-based livestock system, seeks to develop ES at field, farm (soil–plant–animal), or landscape levels. It requires developing diversified place-based farming systems that provide a high level of ES and enable a drastic decrease external input use. It attempts to reposition agriculture in the heart of local ecological, social, and economic systems and development. It favors development of traceable marketing and economies of scope at the farm and/or local levels and interactions (exchanges) between complementary farming systems at the local level. It strongly differs from productivist agriculture due to its goal to develop the different forms of biodiversity and a local eco-economy (Duru et al., 2015b).

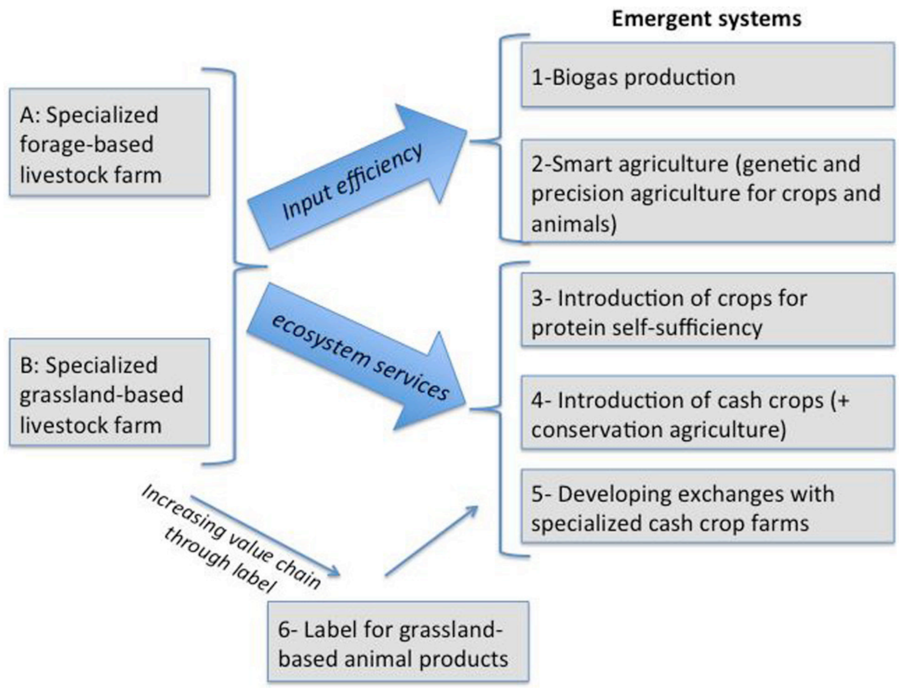


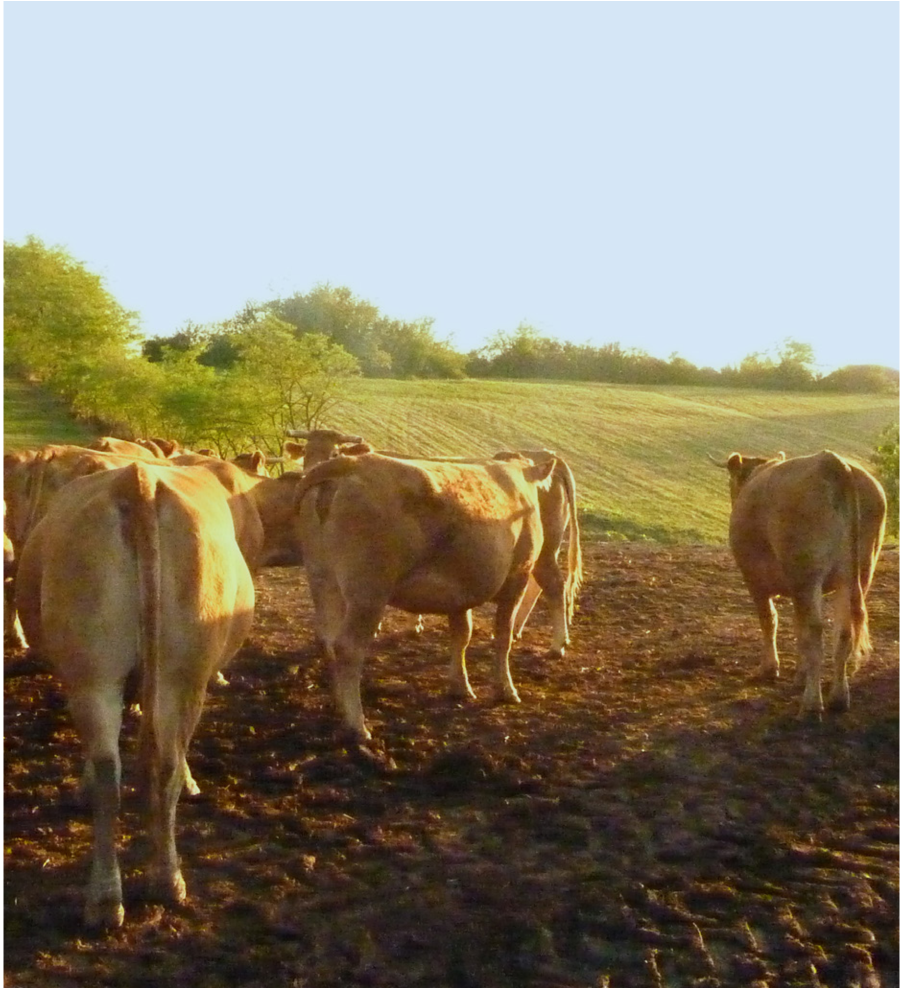
Figure 4. Two main pathways to improve sustainability of specialized livestock farms.

Usually, these two ecological modernization pathways are not clearly distinguished in literature that addresses "ecology-based alternatives" of livestock systems (e.g., Dumont et al., 2012). Nonetheless, the underlying principles (detailed in the following section), the nature of changes (e.g., land use), and the potential impacts are fundamentally different. They also require a different social system, either structured by standards of regional to global markets or a local agricultural innovation system (Duru and Therond, 2014). We claim that these two modernization pathways must be differentiated to clarify and support debate about and development of more sustainable livestock systems. The variety of possible livestock systems that emerge through these two modernization pathways can be understood and represented through the social-ecological approach proposed above.

Scenarios of Ecological Modernization of Ruminant Livestock Systems

Current situation and emergent scenario

For illustrative purposes, we present six ecological modernization scenarios for two types of specialized ruminant farms (A, B on Fig. 4) corresponding to examples of the above-presented pathways (i.e., efficiency/substitution-based and biodiversity-based systems). In intensive agricul-



Grazing cattle cows in an autonomous integrated crop-livestock farm: Southwest of France (source: J. Ryschawy Enat).

Table 1. Comparison of conventional dairy farms and "sustainable dairy farm networks" (CIVAM, a type of biodiversified livestock system in Brittany, France)

Domain	Criteria	Conventional	CIVAM
Structure	Agricultural land (ha)	71	64
	Animal units (dairy cows)	96 (48)	75 (49)
Land use	Stocking rate (number of animal units per ha)	1.61	1.28
	Land use in percentage (grassland/maize/crops)	58/21/21	69/12/19
	Maize for silage (% of forage area)	37	12
	Hedgerows (linear m/ha)	No obligation	>150
Economy	Inputs (euros/ha)	240	100
	Milk/cow (kg)	6,636	5,749
	Food cost (euros/1,000 L)	120	78
	Mechanization cost (euros/ha)	500	400
	Farm income (euros)	157,309	134,718
	Gross operating profit (euros)	42,291	53,365
Environment	Pesticide treatment frequency for maize*	1.66	0.83-1.24
	GHG emissions (kg eq CO_2/1,000 L) †	1100	1100
	Net GHG emissions (kg eq CO_2/1,000 L)	1018	874
Food security	Fatty acids: Omega-6/3	6	3

* Number of applications with standard approved doses.

† Fewer CH4 emissions for conventional farms; more C sequestered for CIVAM farms due to grasslands and hedges; GHG: greenhouse gas.

tural zones, forage-based livestock farms (A) are currently the dominant system, whereas grassland-based farms (B) most often exist as a residual and declining system.

For efficiency/substitution-based systems, sustainability increases through recycling wastes to decrease losses and improve nutrient recycling, such as using manure to feed a biogas production system (Fig. 4, scenario 1) or increasing input-use efficiency through improved plant and animal genetics and precision agriculture, i.e., smart agriculture (scenario 2). Compared with the current situation, this does not induce changes in land cover even in land use at the farm level. Economic organizations and institutions in the current sociotechnical regime strongly support this dynamic, which is based on a linear top-down transfer of standardized technologies, top-down monitoring and regulation, a globalized export- and component-based market, private and public food safety regulations and globalized standards, and power concentrated in large retailers. This socio–economic regime creates lock-ins (e.g., regulatory barriers) for non-standardized and place-based products (Duru et al., 2015b).

Biodiversity-based systems, in addition to the principles of waste recycling and optimizing input use, develop and manage a high level of biodiversity from field to landscape levels to provide regulating services (Duru et al., 2015a). Regarding livestock systems, one strategy is to (re)introduce legumes and grasslands to encourage self-sufficient animal feeding (especially protein) and soil fertility (scenario 3). An extensive strategy is conservation agriculture with grazed cover crops. In this option, cover crops feed ruminants (mostly for beef production) at a lower cost while improving regulating ES (scenario 4). Another scenario consists of developing exchanges of raw products between specialized crop and livestock farms at the landscape level (scenario 5). This offers crop farms the opportunity to introduce legumes and grasslands in rotations or to benefit from manure (compost) produced by livestock farms while the latter have the opportunity to (re)introduce or increase grazed grasslands. These types of livestock systems, particularly scenarios 4 and 5, are place and space based. In these systems, addressing the high level of uncertainty in relations between practices and ES requires the development of a local innovation system based on local stakeholder participation, knowledge sharing, and collaboration. Their development may be highly interdependent on and integrated into the local social, cultural, and ecological rural system, i.e., associated with the development of "territorial biodiversity-based agriculture" (Duru et al., 2015b). The most emblematic forms are sovereign and autonomous local food systems based on "tight feedback loops" that link producers, consumers, and ecological positive effects, for example, through labeled products (scenario 6).

Several illustrations

Comparison of current situation A to scenarios 2 & 3: example of dairy farm dynamics in Brittany (northwest France). Since the 1950s, the high local concentration of intensive livestock systems has induced strong economic and social development, which has also prompted public concern about human health hazards, food security, and environmental problems. The French government has established targets and specific regulations to decrease environmental impacts based on scientific recommendations and national, European (e.g., EU Water Framework Directive), and global (e.g., Kyoto Protocol) regulations and policies (Acosta-Alba et al., 2012). Two main farm dynamics that correspond to both modernization pathways are observed.

The main and more developed path, supported by the dominant agricultural political movement, encourages farmers to optimize input use through improved genetics and decision-support tools to better manage N fertilizers and animal feeding. Some farms are involved in this form of ecological modernization (scenario 2), but others have not yet joined the movement (current situation A). Another option is supported by farm networks called CIVAM (RAD, 2013), which promote sustainable agriculture by implementing innovative ways to develop agriculture and rural activities as part of sustainable territorial development (scenario 3). They strictly limit input use and increase self-sufficiency through diversification of grassland species (legumes), adaptive management of grazing, and long and diversified rotations. These networks promote the development of grassland-based and biodiversity-based livestock systems (Table 1). Their relative number remains low, but the trend is increasing. Farmers seek autonomy in decision-making by developing their own technical reference framework. They are more familiar with self-organization, reflective analysis, and sharing experiences than most farmers involved in conventional dairy systems. The local innovation system that sustains these networks is based on collective experimentation, social learning, and participation in defining collective objectives and specifications of alternative livestock systems. To develop soil fertility, they commit to obtaining 75% of forage resources from grasslands, applying less than 50 kg/ha of synthetic N fertilizer on grasslands, no bare soil in winter, a rotation length of at least 4 yr, and only a small area of silage maize. Farmers also have to develop or protect hedgerows (Table 1).

Table 1 presents a multi-criteria assessment of conventional and CIVAM farms. These latter have lower milk production per cow but higher economic results due to lower costs of inputs and

Crops on pastures in a hill area: Southwest of France (source: J. P. Choisi Inra).

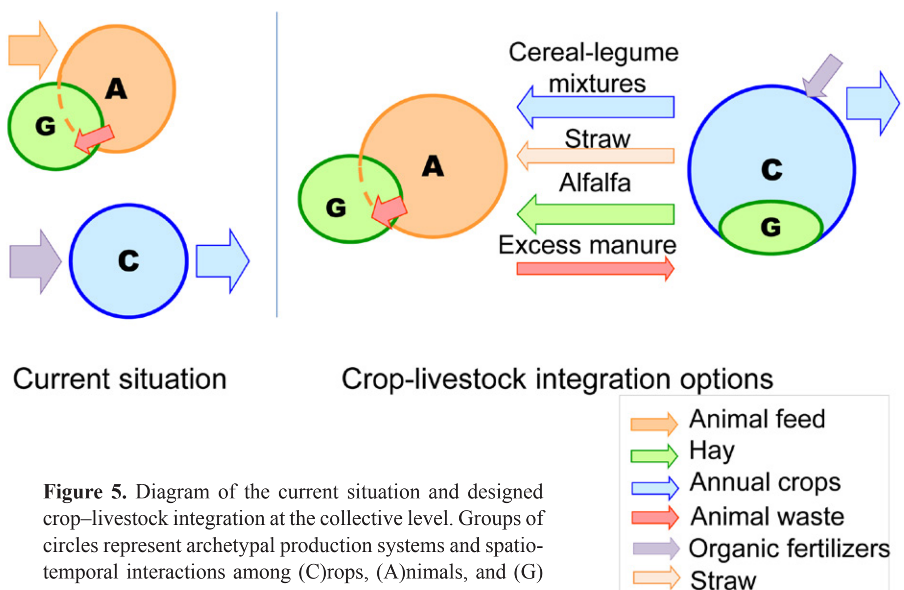


Figure 5. Diagram of the current situation and designed crop–livestock integration at the collective level. Groups of circles represent archetypal production systems and spatio-temporal interactions among (C)rops, (A)nimals, and (G)rasslands. The size of arrows represents the importance of flows between production systems. In the designed situation, use of organic fertilizers exogenous to the collective decreases on crop farms due to transfer of excess manure from livestock systems in the collective.

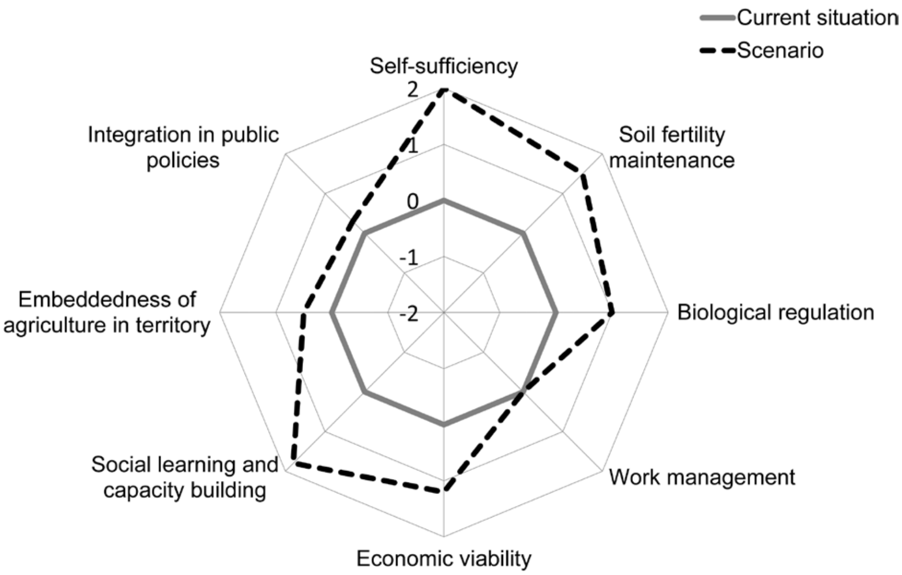


Figure 6. Multi-criteria assessment of the crop–livestock integration scenario. The current situation is considered as the reference, rated null for every criterion. The designed scenario is rated null if it has the same effect as the current situation on the criterion, +1 or +2 if it slightly or strongly improves the criterion, and -1 or -2 if it slightly or strongly degrades the criterion.

mechanization. However, land required per cow is higher, and even more so per kilogram of milk produced. Clear differences are found in the number of pesticide applications, but differences in greenhouse gas (**GHG**) emissions are small. CIVAM farms have clear environmental advantages only when assuming C sequestration by their large areas of semi-permanent grasslands.

From current situation B to scenario 5: participatory design of a collective integrated crop–livestock system to improve autonomy of an organic farmers' group. While crop–livestock integration is recognized as a way to develop more sustainable farming systems, returning and conserving animals on certain farms remains highly challenging. Crop–livestock integration may be developed through organized exchanges between fully or relatively specialized farms at the local level (Moraine et al., 2014). However, development of such collective crop–livestock systems raises technical, organizational, and coordination issues. To illustrate the expressive power of our analytical framework, we briefly present the outcomes of a participatory design-and-assessment process that was conducted with a collective of farmers to generate alternative crop–livestock interactions between farms (Moraine, 2015). During the process implemented in southwestern France, 24 farm surveys and collective workshops facilitated a shared analysis of potential complementarities between farming systems specialized in crop or livestock production to increase self-sufficiency at the collective level (Fig. 5).

When designing interactions between farms, farmers progressively decided to focus on the most realistic land-use options: development of alfalfa and cereal–legume mixtures on crop farms, already produced by few livestock and crop farms, and straw–manure exchanges (Fig. 5). They were reassured by the fact that some of them already have skills and knowledge about these types of production. These options could decrease the importation of exogenous organic fertilizers into cropping systems and promote feeding animals with local products (Fig. 6). Exchanging products in feeding systems decreases feed costs for ruminant systems (by approximately €150 per livestock unit). Multi-criteria assessment of the scenario demonstrates the complementarity of crop and livestock farms, potential enhancement of soil fertility and biological regulation services, contrasting but globally positive socioeconomic performances, and moderate impacts on social embeddedness at the territory level. Farmers were able to progressively refine the designed collective interactions due to the iterative design-and-assessment cycle, which was based on using our analytical framework and an original multi-criteria grid that addresses the metabolic efficiency (nutrient cycling), ecosystem services, work management, capacity-building, and local embeddedness of farming systems (Fig. 6).

Conclusion: Toward a Common Understanding of Land-Use Principles

Dominant livestock farms in intensive production zones in Europe, and more broadly in developed countries, are often specialized to increase economic efficiency through economy of scale. Their environmental impacts, health concerns, consumer preferences, and sustainability of production require a change in livestock systems toward more ecological practices. Livestock sustainability can be enhanced through two main ecological modernization pathways (efficiency substitution or biodiversity based) that have different impacts on land use in terms of the degree, scale, and nature of changes. Individual stakeholders and economic and social organizations can foster one or the other pathway according to their viewpoint and interest. Therefore, a structured representation of livestock systems as social-ecological systems, highlighting key interactions among grasslands, crops, animals, farmers, actors in the supply chain, and natural resource managers, may help stakeholders to identify current sustainability issues and the possible future of livestock systems. Our conceptual framework enables the development of such representations and can be used accordingly to support stakeholders in identifying biophysical, technical, and social interactions that promote synergies and address trade-offs between ecosystem services and socio–economic performances. It also may be used to support stakeholders in characterizing the nature of different pathways to more sustainable livestock systems: optimizing input use without changing animal and crop diversity or managing and increasing crop and animal biodiversity at field, farm, and landscape levels to promote ecosystem services.

The use of our framework does not produce a model of ecological modernization but enables clarification of key differences in current and possible future systems, the domains of sustainability they impact, and the social system in which they are embedded. According to the ecological modernization pathway, social organization may corresponds either to an evolution of the current dominant regional-to-global socio-technical regime that supports development of the bioeconomy or to a locally structured agri-food innovation system that seeks to develop an eco-economy. Augmented with a multi-criteria grid adapted for certain criteria (e.g., resilience, robustness, and sovereignty), this framework can help stakeholders involved in design-and-assessment of acceptable and realistic sustainable farming systems.

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