Reg Environ Change (2015) 15:1651–1665
DOI 10.1007/s10113-014-0722-9



ORIGINAL ARTICLE

# Livestock system sustainability and resilience in intensive production zones: which form of ecological modernization?

**Michel Duru · Olivier Therond**

Received: 10 January 2014 / Accepted: 3 November 2014 / Published online: 25 November 2014


**Abstract** Changes in agriculture during the twentieth century led to high levels of food production based on increasing inputs and specialization of farms and agricultural regions. To address negative externalities of these changes, two forms of ecological modernization of agriculture are promoted: "weak" ecological modernization, mainly based on increasing input efficiency through crop and animal monitoring and nutrient recycling, and "strong" ecological modernization, based on increasing agrobiodiversity at different space and time scales and within or among farms to develop ecosystem services and in turn reduce industrial inputs even more. Because characterizing the sustainability of these two forms of ecological modernization remains an issue, we review the literature on livestock systems to compare their advantages and drawbacks. After defining the livestock system as a local social–ecological system embedded in a complex multi-level and multi-domain system, we characterize the two forms of ecological modernization (weak vs. strong). When sustainability is defined as a state that should be maintained at a certain level and assessed through a set of indicators (environmental, economic, and social), we highlight that one ecological modernization form might have an advantage for certain sustainability criteria, but a disadvantage for others. When sustainability is viewed as a process (resilience), we find that these two forms of ecological modernization are based on different properties: governance of the entire agri-food chain for weak ecological modernization versus local governance of agriculture and its biophysical and social diversity and connectivity, and management of slow variables for strong ecological modernization. The relevance of this sustainability-analysis approach is illustrated by considering different types of dairy livestock systems, organic agriculture and integrated crop–livestock systems.

**Keywords** Agri-food chain · Agroecosystem · Dairy farm · Ecological principle · Innovation · Profitability

Editor: Nicolas Dendoncker.

Michel Duru and Olivier Therond are the Co-first authors.

M. Duru · O. Therond
UMR 1248 AGIR, INRA, 31326 Castanet Tolosan, France
e-mail: therond@toulouse.inra.fr

M. Duru (✉) · O. Therond
INPT, UMR AGIR, Université Toulouse, 31029 Toulouse, France
e-mail: Michel.Duru@toulouse.inra.fr; mduru@toulouse.inra.fr

## Introduction

The model of productivist agriculture, based on the use of synthetic inputs and natural resources to minimize the effects of limiting production factors and environmental heterogeneity, and on genetic improvement of plants and animals enabled a massive increase in agricultural production. In most areas without strong environmental constraints, it is accompanied by mechanization, simplification and standardization of production modes, a decreasing diversity of crops and livestock breeds, and the creation of uniform landscapes. It has often led to geographical separation of cropping systems and livestock systems (Lemaire et al. 2011). In the logic of economy of scale and expression of comparative advantages (e.g., for soil fertility, climate, knowledge, labor costs, infrastructure, and regulations), it has led to the specialization of farms and regions within countries (e.g., dairy farms in Brittany for

France) or between countries (e.g., Europe imports South American soybeans as animal feed). The objective of increasing health safety and standardization of agricultural production has strengthened this specialization process (Horlings and Marsden 2011; Lamine 2011).

This model of productivist agriculture expanded greatly after the Second World War in Western countries. However, in the 1980s, awareness emerged about its negative effects on biodiversity and climate change, but also on product quality, human health, and depletion of fossil and water resources, which influences resource scarcity. More particularly, livestock systems have been blamed for their effects on water pollution, competition for food, and emission of greenhouse gases (nitrous oxide, methane) (FAO 2006; Janzen 2011). At the same time, the development of political concerns about sustainability and multifunctionality has redefined the objectives assigned to agriculture through agricultural policies. Good agricultural practices reducing negative impacts of agriculture, development of planned biological diversity, and conservation of high-value natural systems, and areas have become key targets of these policies. Regarding geographical specialization, the conservation and even the development of livestock systems in crop-oriented zones is becoming a challenge, at least in Western Europe and the USA (Lemaire et al. 2014). Livestock can both stress and benefit ecosystems. Environmental problems lie not so much with the animals themselves but rather with how they are integrated into agroecosystems and food systems (Gliessman 2006). The current consensus seems to be that agriculture that includes livestock production should adapt to produce ecosystem services that benefit human well-being (Janzen 2011). Provisioning services, such as supply of plant and animal products, depend on supporting and regulating services, also called input services (Lamarque et al. 2011), such as soil fertility, nutrient cycling, water provision, pest control, and pollination. They can also favor provision of non-market services such as climate change mitigation, wildlife habitat, and recreational landscapes (Zhang et al. 2007; van Oudenhoven et al. 2012).

In the late 1990s, Morris and Winter (1999) advocated a third path for European agriculture, called "Integrated farming systems," which is based on ecological principles that could be used along with conventional and organic practices. This analysis has recently been expanded, distinguishing two main forms of ecological modernization of agriculture according to whether or not they are based on agrobiodiversity and related ecosystem services (Horlings and Marsden 2011). First, "weak" ecological modernization of livestock system ("weak-EMLS") primarily aims to reduce their main negative impacts by increasing resource-use efficiency. It is based on implementing good agricultural practices (Ingram 2008) and recycling waste (Kuisma et al. 2012). It may also be based on using new technologies such as precision agriculture (Rains et al. 2011), biofertilizers (Singh et al. 2011), and genetically modified organisms. It does not call into question the specialization of farms and landscapes and the associated drastic reduction in the number of cultivated species or breeds. Second, "strong" ecological modernization of livestock system ("strong-EMLS"), in addition to the principles of waste recycling and input-use optimization, aims to develop diversified farming systems (Kremen et al. 2012), developing and managing biodiversity in agroecosystems at different organizational levels to provide supporting and regulating services that determine provisioning services. Based on biodiversity development, strong-EMLS also favors non-market services. These services depend on practices implemented at the field and farm levels, but also, importantly, at the landscape level (Power 2010). Usually, these two forms of ecological modernization are not clearly distinguished in the literature dealing with "ecology-based alternatives" for livestock systems (e.g., Dumont et al. 2012). As underlying principles, which are detailed in the following section, the nature of changes and, therefore, the potential impacts of these two forms of EMLS are fundamentally different. We assert that they should be differentiated when examining sustainability of future livestock systems.

Sustainability has two traditional meanings: a (system) state that should be maintained at a certain level and the ability (of the system) to sustain. Regarding the former, for agriculture, this often expresses the state in which agricultural production levels are maintained within the capacity of the ecosystem supporting it (Kajikawa 2008). Used in this way, it converges with the WCED's (1987) definition of sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." Most often, methods that assess sustainability of a "snapshot" state of agricultural systems use sustainability indicators covering the three pillars of sustainable development (i.e., environmental, economic, and social). Conversely, resilience thinking offers a vision of sustainability as a process for examining how to maintain system functioning in the face of perturbations (Folke et al. 2002). It is both related to resistance to changes and maintenance of current states, as well as adaptive renewal leading to new states when new characteristics of the context (e.g., shocks) require redirecting the system (Walker et al. 2004). While sustainability focuses on reaching pre-defined outcomes, resilience focuses on adaptive capacity (Anderies et al. 2013). Resilience is a conceptual framework for understanding how complex systems self-organize and adapt to changes over time. Importantly, it is a system-level concept that is useful for identifying human and material capitals needed to cope with unknown futures. Assessing resilience leads to answering two key questions: resilience of what (which system and which properties) and resilience to what (which perturbations). While most studies of resilience of agricultural systems assess whether they are able to maintain their essential attributes and functions within and across organizational levels despite changes in specific components or activities, Jackson et al. (2010) suggested focusing on actors' capacities to meet their needs in new ways instead of remaining in current trajectories. However, dynamic assessment of resilience is rarely explored for livestock system, although it is the main way to examine a system's adaptive capacity and trade-offs among services (Turner 2010).

The objective of this paper is to provide an integrated analysis of livestock systems in regions where specialization and intensification of agriculture has led to negative environmental impacts and that are now seeking forms of ecological modernization to reduce these impacts while maintaining or increasing agricultural production. Focusing on ruminants, we compare throughout the paper, strong and weak forms of EMLS considered as two archetypal forms of ecological modernization corresponding to the two ends of a continuum. First, based on the multi-domain and multi-level (local vs. global) grid of Darnhofer et al. (2010a, b), we define a livestock system as a local "social–ecological" system and then present the main characteristics of the two forms of EMLS. Second, we assess sustainability of these two forms of ecological modernization with sustainability indicators and analysis of governance and properties of livestock systems, i.e., their resilience. Finally, we illustrate our comparative analysis by applying it to case studies (dairy farms and a variety of others) which are akin to the two archetypes of livestock systems. To do so, we examine whether those that exhibit the main features of strong ecological modernization (management principles and system performances) exist in these case studies.

## Characterizing the diversity of livestock systems

### Livestock systems within a complex multi-level and multi-domain hierarchical system

Livestock systems are embedded in multi-level and multi-domain agricultural systems. They can be represented as a complex hierarchical nested system structured by different domain hierarchies: ecological and biological, economic, and social. Nested organizational levels of these hierarchies are composed of multiple subsystems (ten Napel et al. 2011) (Fig. 1).

At the bottom agricultural levels, farms and farmer networks (the farm community) are the key subsystems (Fig. 1, bottom line). They shape the ecosystem including crops and animals (Fig. 1, left column), which are managed to produce food for society and income for farm families (Fig. 1, middle column). The cultivated ecosystem provides provisioning and non-market services according to local-to-global biophysical dynamics and farmer management practices. As for other economic actors, farmers' behavior depends on the ecological context, agri-food chain(s), and social and political contexts in which farmers and their agricultural activities are embedded. All of these shape farmers' individual lifestyles (Vanclay 2004): values, preferences, representation of farming system state and functioning, objectives, and associated strategies. The extent to which farmers seek to change their farming systems through weak or strong ecological modernization logic is represented in Fig. 1 (right column).

Interactions between subsystems of the hierarchical nested system occur within levels (e.g., farm level) and between levels and domains via biophysical and socio-economic processes (e.g., nutrient flows, management practices, social interaction, and economic organization) (Darnhofer et al. 2010a, b; Jackson et al. 2010; Ewert et al. 2011). For example, the status of the global sub-system (e.g., climate change) depends on the aggregated effects of land-use and management practices, which in turn affects vegetation dynamics at the farm level and possibly environmental policies at national or regional levels. At the farm level, interactions across ecological, economic, and social domains determine agricultural practices. Interactions occur also across time scales at the field level (e.g., cumulative effect of soil management techniques on soil fertility and structure) and at higher levels (e.g., nitrogen cascade).

This representation of agricultural systems enables us to define boundaries of livestock systems investigated here. We follow Cabell and Oelofse (2012), who defined a livestock system (hereafter called "agroecosystem") as "an ecosystem managed with the intention of producing, distributing, and consuming food, fuel, and fiber. Its boundaries encompass the physical space dedicated to production, as well as the resources, infrastructure, markets, institutions, and people that are dedicated to bringing food to the plate, fiber to the factory, and fuel to the hearth." Given this definition, the system encompasses all the complexity of a "social–ecological system." Below, we focus our analysis at the local level, where farmers, farmer communities and, potentially, local market organization determine land use and land cover and accordingly their diversity and sustainability. In our approach, the levels above the local level are the (external) environments of the livestock systems. Of course, the livestock system is an

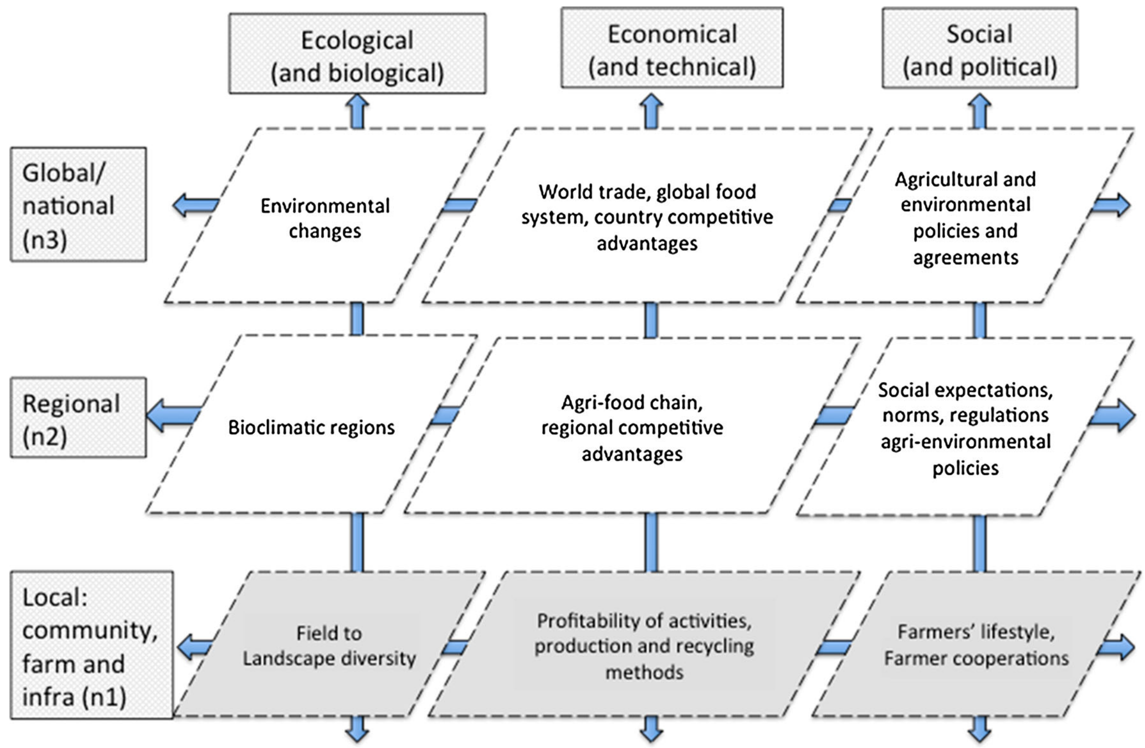


**Fig. 1** Agriculture as a complex, hierarchical multi-domain system whose emergent properties depend on interactions within and between local, regional, and national/global levels (levels *n1*, *2*, *3* in *lines*) and ecological, economic, and social domains (*columns*). Main features of sub-systems by domain and organization level are presented. *Gray cells*, the local level, correspond to the livestock system as defined in the paper. It includes communities, farms, and ecosystems (crop, animal, and habitat diversity). Adapted from Darnhofer et al. (2010a, b)

open system that exchanges energy, material resources, and information (resources) with its environment. Livestock systems involved in weak or strong ecological modernization differ greatly in the nature and intensity of internal biophysical and socioeconomic processes and interactions with their environment.

## Weak and strong ecological modernization of livestock systems

Over the past few decades, a general decrease in agricultural market prices (and thus in profit per unit), especially for animal products, and amortization of large farm investments have pushed farmers to increase farm size and seek the least expensive inputs from the world market (e.g., Argentine or Brazilian soybeans for European livestock farms). Through economies of scale, the agri-food sector has sought to decrease costs of inputs (e.g., seeds, animals, and feeds), production collection (e.g., milk), and stock (e.g., grain) and, consequently, has organized strong standardization and limitation of a variety of proposed agricultural inputs and products by farmers. Consequently, farming systems and practice specialization, standardization, and simplification have been strongly influenced by regional-to-world-scale markets and weakly influenced by local issues and local farmer interactions. Over the past several decades, agriculture has been perceived as a separate and independent sector and not as integrated into the local social–ecological system (Leat et al. 2011).

Weak-EMLS aims to limit negative effects of agricultural activities on the environment and the depletion of natural resources (Table 1, lines 2–5). Farmers implement weak ecological modernization mainly to comply with environmental regulations and "command and control" policies or to take advantage of policy incentives such as agro-environmental measures of the European Common Agricultural Policy. The weak ecological modernization process does not modify the main logic that underpinned farming system functioning. They are still greatly dependent on and driven by regional and international markets: "Economic sustainability is the foremost concern for the businesses involved, with progress on other dimensions of sustainability being developed from positions of economic viability" (Leat et al. 2011). This agricultural model tries to address sustainability issues through intensive use of "one-size-fits-all" solutions (Table 1, last line).

In contrast, livestock systems that implements a strong ecological modernization seeks to develop place-based

**Table 1** Features of the two paradigms of ecological modernization of livestock system (EMLS)

| Feature | Weak-EMLS | Strong-EMLS | Main references |
|---|---|---|---|
| Main aim | Reducing negative environmental impacts | Producing ecosystem services for saving resources | Marsden (2012) |
| Economical integration | Agri-food chain integration; export oriented; used of external resources | Locally embedded in the community | Horlings and Marsden (2011) |
| Governance and innovation system | Top-down steering and regulation; power concentrated at multinationals and large retailers based on notions of "free-trade" | New innovation sharing and collaboration; self-sufficiency in the context of fair trade; agri-food networks | Horlings and Marsden (2011), Klerkx et al. (2012) |
| Technological and ecological principles; land use | Top-down and one-size-fits-all: genetic improvement, good management practices, precision farming, recycling technologies<br>Limited number of crops | Place-based and biologically diversified farming system; multiple crops or subsystems interacting; use and reproduction of local resources<br>Ad hoc spatial and temporal «planned» diversity promoting «associated» diversity | Altieri et al. (2011), Duru et al. (2014) |
| Main necessary capital | Financial and material | Human and material for implementing place-based practices | |

agroecological systems that provide ecosystem services to drastically decrease use of external inputs (Table 1, lines 2–5). These farming systems are based on diversification of crop and sometimes animal species within farms. As highlighted by Marsden (2012), this agriculture form attempts to reposition agriculture into the heart of regional and local systems of ecological, economic, and community development. Strong-EMLS is based on economies of scope at the farm and/or local levels and a traceable market and take advantage of potential production complementarities of farms at the local level. Livestock farms may buy some of the diversified production of local crop farms (e.g., protein crops) rather than raw materials from national or world markets (e.g., industrial food, soybeans from other continents). This diversified local market may support development of more autonomous livestock systems (including decision-making autonomy) than weak-EMLS, insofar as they depend less on the global context for inputs (due to ecosystem services or local exchange) and product processing and marketing (Altieri et al. 2011). However, since farmers implementing strong-EMLS must manage biodiversity at different levels (field, surrounding fields, and landscape), they encounter more complex adaptive systems than those implementing weak-EMLS (Kremen et al. 2012). To develop new place-based agroecological practices with few preexisting references and the need for social coordination at the landscape level, they must implement renewed systems of agricultural innovations and build grassroots networks (Klerkx et al. 2012).

Weak-EMLS farms are embedded into larger agri-food chains more than strong-EMLS farms because the networks of people, resources, infrastructure, markets, and institutions that are dedicated to transporting natural resources and synthetic inputs to farms, factories, and retailers are potentially much larger. The more that inputs and natural resources are difficult to access (due to high price or regulations), the more the context will be favorable for strong-EMLS, which may cause sustainability problems for weak-EMLS. In the same logic, regional-to-global policies that mainly support either specific local markets or standardization of products for export will favor the emergence of niches that are based on strong-EMLS principles (Geels 2002) or regimes that promote weak-EMLS.

Continuing the productivist model, weak-EMLS is the dominant sociotechnical regime, i.e., a relatively stable configuration of institutions, techniques, regulations, standards, production norms, practices, and actor networks (Geels 2002). It is dominant because of its ability to create technological, organizational, and institutional "lock-in" that ensures its persistence (Vanloqueren and Baret 2009). In contrast, strong-EMLS can be considered as production niches, i.e., unstable configurations of formal and informal networks of actors in which radical innovations emerge (Horlings and Marsden 2011). Depending upon biogeographical, economic (agri-food chains), social (actor networks), and political contexts, most livestock systems follow either weak- or strong-EMLS, from confinement systems to grassland-based and mixed crop–livestock systems. The form of ecological modernization followed strongly determines the nature and degree of the connectedness of livestock systems to farmland. Each form of ecological modernization may have strengths and weaknesses in sustainability and resilience at field-to-farm and local-to-global levels.

Innovation rationales of weak and strong ecological modernization of livestock systems

Weak-EMLS aims to continually improve crop and animal performances (quantity and quality) while reducing undesirable emissions (Fig. 2) and sometimes sensitivity to environmental hazards (e.g., drought, pests). It is based on an industrial ecology paradigm that aims to optimize exchange between subsystems of the entire production system to improve resource-use efficiency and waste recycling (Figuière and Metereau 2012). A main objective is to improve the "degree of circularity" of material and energy resources through recycling, which directly reflects the level of resource-use efficiency. An increase in the degree of circularity would be, for example, to shift from using manure directly as fertilizer to using biogas slurry as fertilizer (Tauseef et al. 2013). Some innovations consist of organizing recycling at the landscape level, for example, by exchanging manure (Asai et al. 2014) or by collecting complementary types of waste for biogas production (Sorathiya et al. 2014). Technology-based precision livestock farming is one pathway to increase resource-use efficiency. In dairy production, for example, radio-frequency identification tags signal computer-controlled self-feeders to adjust concentrated feed to optimize individual daily potential milk production, while milking robots, which measure actual milk production, allow cows to schedule their own milking (Gebbers and Adamchuk 2010). Some innovations based on remote sensing for operational crop monitoring must be organized at a regional level to process and disseminate information at low cost. Another example is the possibility to reduce ammonia emissions

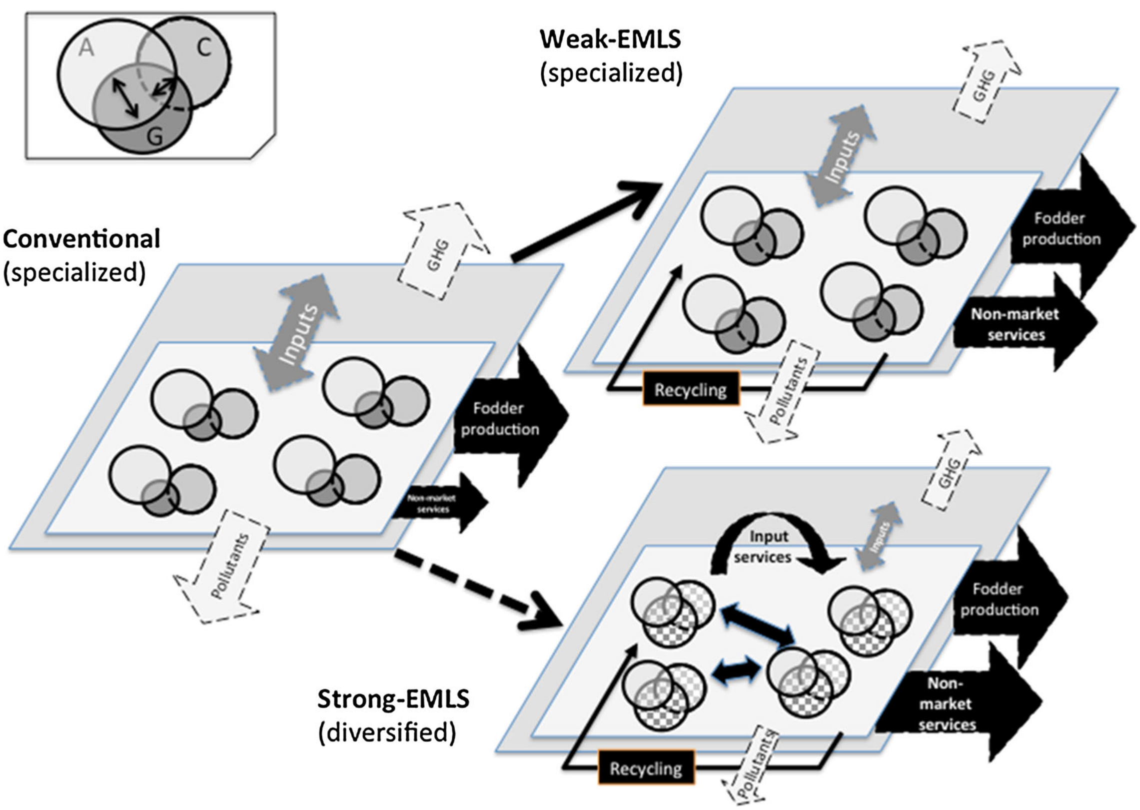


**Fig. 2** Two forms of ecological modernization of conventional livestock systems, focusing on land use. Weak ecological modernization of livestock system (EMLS) is the current mainstream. Local livestock systems and regional–global levels of the agri-food chain are represented by *light gray* and *dark gray trapezoids*, respectively. The *figure at the top left* represents a farm composed of one or more activities symbolized by *circles* that overlap slightly (weak-EMLS) or greatly (strong-EMLS) representing (C)rops, (G)rasslands, and (A)nimals. *Degrees of overlap* represent degrees of temporal and spatial interactions between these activities (e.g., grassland in rotation with crops, grazing of grassland, and/or crop residues). In weak-EMLS, technology-based practices increase input-use efficiency, and recycling reduces input use and disservices [pollutant and greenhouse gas (GHG) emissions to the environment]. In strong-EMLS, species mixtures (*checkered circles*) are grown in arable (crop) land and grassland, exchanges between farms increase, and agroecological practices provide input services that in turn can reduce use of exogenous inputs. For readability, the fact that weak-EMLS and strong-EMLS systems can coexist at the local level is not represented

by storing manure in sealed tanks and then covering it after field application.

For strong-EMLS, the supply of ecosystem services crucially depends on maintaining biodiversity through adapted management in space, time, and intensity (Altieri and Nicholls 2004; Hooper et al. 2005) (Table 1, last line). Strong-EMLS is based on the management of planned biodiversity (e.g., domestic plants and animals), the soil and landscape matrix to promote beneficial nutrient cycling and associated biodiversity (e.g., soil microbes, flora and fauna, and insects) and, directly or indirectly, ecosystem services. It is part of a middle- to long-term process in which adapted soil and landscape properties are developed. Farmers must manage biodiversity across spatial scales, from fields (crop mixture), areas around crop fields (e.g., hedgerows, grass strips) to neighboring fields (e.g., mosaics of crops and land-use practices) and the landscape (e.g., cropping system pattern, landscape matrix, woodlots, seminatural areas). Across temporal scales, reduced soil tillage, cover cropping, and crop rotations favor soil fertility and within-field bioregulation. At the landscape scale, asynchronous tilling, planting/sowing, harvesting, cover cropping, and crop rotations contribute to maintaining the heterogeneity that promotes associated biodiversity (Shennan 2008). Regarding ruminants, diversity can be promoted by raising different breeds of the same species or different species. Mixed-species stocking offers potential advantages for animal health (e.g., more effective parasite management) and crops (e.g., more uniform use of plants) (Anderson et al. 2012). Integrated crop–livestock systems offer opportunities to increase ecosystem services via spatial and temporal interactions between animals, crops, and grassland (Fig. 2). For example, at the farm level, grazing crop residues (Martens et al. 2011) or manure application increases diversity of microbial and invertebrate communities in soils, which in turn promotes nutrient cycling (Reganold et al. 2010). Grazing of intercrops can enhance physical, chemical, and biological soil fertility, especially in cropping systems where pastures are grazed (Sulc and Franzluebbers 2013) or when combined with no-till farming (Franzluebbers and Stuedemann 2013). Crops and livestock can also be integrated at the local level, through farm exchanges and interactions aimed at creating local diversified marketing channels adapted to the region and optimizing the use of individual farm resources (i.e., to grow crops or animals best suited to a given characteristic, such as soil conditions) (Sanderson et al. 2013). One of the great challenges of strong-EMLS is developing local coordination for land use within a region that best expresses biological regulations, pollination services, and, if necessary, interactions and exchanges between farms.

## Sustainability of livestock systems

### Sustainability of livestock systems as a state issue

We use well-identified sustainability indicators for livestock systems (e.g., Lebacq et al. 2012) to assess sustainability performances of the two forms of ecological modernization (Table 2). For environmental criteria, strong-EMLS by nature performed better for biodiversity, biological soil fertility, and C sequestration, due to characteristics such as greater proportion of (semi-)permanent grasslands and cover cropping on the farm and/or diversified crop sequences possibly including grasslands. For nitrate losses, indoor cow feeding (weak-EMLS), in which transformation of waste and its application to soil can be fully or almost fully controlled, can perform better than

**Table 2** Qualitative assessment of sustainability of livestock systems when shifting from conventional to weak and strong ecological modernization (EMLS) over the current context [adapted from Lebacq et al. (2012)]

| Domain | Criteria | Weak-EMLS | Strong-EMLS |
|---|---|---|---|
| Environment | Biodiversity | =/− | ++ |
| | GHG (chemical inputs, energy consumption) | + | ++ |
| | GHG (methane) | + | + |
| | Soil C storage | =/− | + |
| | Soil quality | | |
| Economy | Profitability | + | + |
| | Autonomy | − (market) | + (local governance) |
| | Risk | + (dependency) | − (due to diversity) |
| | Transmissibility | – | +/= |
| Social | Internal (working condition; quality of life) | +/− | +/− |
| | External (multifunctionality of agriculture) | =/+ | + |
| | Quality of products | ? | ? |
| | Sovereignty | – | + |

+, = , − Improving, maintaining or deteriorating the sustainability criterion considered grazing (strong-EMLS) in some situations (e.g., sandy soil coupled with rainy weather and low temperatures). For $CH_4$ emissions, a detailed description of practices is needed to compare both forms of ecological modernization. For example, feeding cows with silage maize and concentrated feeds tends to have lower $CH_4$ emissions than grass-based feeding systems, especially if linseed is added (Doreau et al. 2011). Both forms of ecological modernization can have a slightly negative or even positive energy balance due to the balance between energy consumption and production (e.g., biogas production or solar-energy capture).

Both forms of ecological modernization can be economically profitable. Even though strong-EMLS may have lower land productivity, its inputs are also lower (e.g., fewer antibiotics, exogenous feeds, pesticides, and fertilizers), so that profit per output unit can increase (Lebacq et al. 2012). Less based on input use, autonomy (in terms of external financing or inputs) is greater for strong-EMLS farms. Income variability may be lower for strong-EMLS farms because they are based on an economy of scope (i.e., diversified production) and thus can spread cash flow over multiple markets. For weak-EMLS, insurance offered by the agri-food chain can reduce risks. Financial capital is generally higher on weak-EMLS farms due to the intensive use of generic material innovations and the often greater farm size necessary to ensure profitability, often with low added value. The human capital required is larger in strong-EMLS, since place-based systems are based mainly on cognitive innovations.

For social criteria, working conditions and quality of life may differ, but each form of ecological modernization may be satisfactory because it depends greatly on farmer preferences and/or lifestyles (Vanclay 2004). However, as underlined by Tripp (2008), agroecological management, which is context dependent, is much more complex and accordingly requires more significant cognitive resources and greater continuous learning. The multifunctionality of agriculture, the capacity to deliver benefits beyond agricultural production, is undoubtedly greater for strong-EMLS (Wilson 2008). Product quality is not simple to compare from a human health perspective. On the one hand, it can be better controlled in specialized and simplified food-chain production (weak-EMLS). On the other hand, strong-EMLS often performs better from the organoleptic viewpoint, especially if animals are fed from natural grasslands (e.g., Coulon et al. 2004 for cheeses), and has a better symbolic picture. To achieve a human-diet profile well balanced in fatty acids, weak-EMLS may add linseed to ruminant diets based on maize and soybean (Glasser et al. 2008), whereas strong-EMLS may focus on grazing-based ruminant diets (Dewhurst et al. 2006). Strong-EMLS offers higher autonomy of farmers to produce healthy and culturally appropriate food through ecologically sound and sustainable methods (Holt-Giménez and Altieri 2012).

## Sustainability of livestock systems as a resilience issue

We address the resilience of livestock systems to changes in social (e.g., consumer behavior, social expectations about agriculture), political (e.g., regulations and norms), economic (e.g., level and variability of input and output prices), and ecological (e.g., climate change, animal health) systems. These changes can correspond to shock, i.e., fast and intensive changes (e.g., price volatility, strong drought, and economic crises), or stressors, i.e., continuous, less intensive changes (e.g., climate change). Defining the livestock systems as a local social–ecological system, and based on Biggs et al. (2012), who deal with principles of ecosystem service resilience, we approach livestock systems resilience according to two key dimensions: governance of the livestock systems and its properties. Here, governance means the social and political processes that shape the management of farms, agri-food chains, and agricultural innovation systems.

### *Governance of livestock systems*

Weak-EMLS is embedded into the dominant regime based on large well-structured networks, institutions, and lobbies that defend its merits and claim the need to concentrate money and effort into large companies with technological developments that require significant monetary resources (e.g., pharmaceuticals, genetic innovations). Farms are usually managed through a planned process in which necessary knowledge about the specific production situation is usually low or acquired through automated and dedicated technologies. In these systems, innovation is a top-down process in which public and private research and development provide farmers with technologies (inputs and materials) to be used in a standardized manner. In this form of ecological modernization of agriculture, the agroecosystem is mainly seen as a "technological system" of production. Local interactions are often limited to sharing material technology.

Managers following strong-EMLS have to cope with uncertainty about biological and ecological processes that generate ecosystem services and partial control (observational uncertainty) over the effects of practices on these processes, especially input services (Williams 2011). The agroecosystem is seen as a complex adaptive system characterized by emergent and nonlinear behavior, a high capacity for ecological and social self-organization and adaptation based on past experiences, distributed social control, and ontological uncertainties linked to incomplete knowledge of managers. Farmers have to develop sitespecific practices and consider the local expression of the processes involved, e.g., plant–animal interactions during grazing (Hodgson 1985), soil–animal interactions to manage parasites during grazing (Dumont et al. 2012), and plant–soil interactions for nutrients (Eviner and Hawkes 2008; Tomich 2010a, b). Most often, farmers incorporate traditional cultivation techniques with modern knowledge (Doré et al. 2011). They practice adaptive management, which consists of active monitoring of and feedback from the effects and outcomes of decisions. In this way, farmers learn that consequential actions are always necessarily specific (Jiggins and Roling 2000). Farmers are organized into grassroots networks and institutions for reflexive analysis and sharing of learning. The on-farm innovation implemented in strong-EMLS is usually collaborative (sharing information through field visits). It is based on developing coordination between actors to co-produce knowledge and technology, possibly supported by participatory and interdisciplinary research (Knickel et al. 2009). This so called agricultural innovation system supports social involvement, i.e., engaging in social exchange.

At the local level, the resilience of weak-EMLS farms depends strongly on the entire agri-food chain and techno-science system, including research. Whether technical or economic impasses appear, due to problems in the ecological system (e.g., biological resistance, pollution, and recurrent and significant diseases) or the social system (e.g., rejection of a technology such as genetic modified organisms, insufficient profit for farmers), the resilience of the livestock system depends fully on the agri-food chain to provide acceptable alternatives. For example, the agri-food chain can offer insurance to ensure the viability of farming systems during abnormal weather years (Vermeulen et al. 2012). In the same vein, weak-EMLS farms can decrease their sensitivity to the price volatility of inputs (e.g., soybean) and outputs (e.g., meat) by signing contracts with pre-defined prices with companies for supplying and with retailers for selling (Gilbert and Morgan 2010). In the strong-EMLS model, adaptations to perturbations may come mainly from farming system diversification, farmers' human capital, and local ad hoc organizations. As mentioned above, strong-EMLS spreads economic and production risks over several different enterprises and thereby benefits from a variety of agricultural markets (Darnhofer et al. 2010a, b; Hendrickson et al. 2008). The grounded networks necessary for sharing knowledge about adaptive management practices are essential for developing strong-EMLS and offer opportunities to develop economies of scope at the local level through local farmers' markets and food cooperatives. This enables organization of exchanges of protein and forage products between crop and livestock farms, for example (Hendrickson et al. 2008). This high cooperation between individuals at the local level also offers opportunities for economies of scale, e.g., through sharing expensive equipment such as direct-seeding machines. In contrast, the strong connection of weak-EMLS to the regional-to-global market often leads to weak local social exchanges and connectivity, and in turn weak local capacity for adaptation to locally grounded changes. In general, beyond a certain threshold of disturbance, a specialized farm based on weak-EMLS may become endangered because incremental technological innovations may no longer maintain profitability or meet environmental standards (e.g., Belgian blue cattle system in Schiere et al. 2012).

More generally, resilience of the two forms of ecological modernization at the local level will depend strongly on trade-offs between economic and social/policy drivers at regional and national-to-global levels (n3 in Fig. 1). In developed countries, this is generally the level at which norms, regulations, taxes, or incentives are established to manage negative and positive externalities and scarce resources.

### *Properties of livestock systems*

Biological and social properties of LS that correspond to the two contrasting forms of ecological modernization are fundamentally different; strong-EMLS relies on developing an agroecosystem with a high level of diversity, redundancy, connectivity and long-term management of slow variables (Biggs et al. 2012).

Diversity corresponds to the number, abundance, and composition of genotypes, populations, species, functional types, communities, and landscape units for the ecological system and of individuals (e.g., farmers), social groups and organizations for the social system. It determines the potential for adaptations to social innovations of and learning about the agroecosystem. Functional diversity and redundancy determine the degree to which substituting one set of components with another can meet a biological or social function. Biological and social connectivity determine levels of possible circulation of material (including organisms, actors and energy) as well as cognitive resources in the system. For example, it determines species' dispersal capacities between habitats (Tscharntke et al. 2005). However, there is a threshold above which diversity can lead to a system whose functioning is cumbersome, complex, less efficient, and has low adaptation capacity. Too much connectivity also can favor massive propagation of initially local perturbations (e.g., diseases) or individualist behavior harmful to the system (Biggs et al. 2012). In weak-EMLS, due to strong biodiversity homogenization, uniform practices (e.g., pesticide use) and the strong links between components of the agri-food chain, potential impacts of pests, diseases and other strong ecological and socioeconomic perturbations (e.g., prion crisis, price volatility, weed resistance) can have a significant effect on sustainability of agricultural systems. In general terms, strong-EMLS, being more autonomous and diversified, has less "tightly coupled" systems and thus a lower risk that accidents become catastrophes for the whole system (Kirschenmann 2010) as well as for their social or their ecological dimensions. Strong-EMLS may resist strong perturbations, such as recurrent droughts, due to complementarities between diversified organisms (e.g., equilibrium among species with differing drought sensitivity in crop and grassland mixtures), increased biophysical capacities (e.g., soil water-holding capacity in conservation agriculture), or breeding of native livestock breeds. By seeking to develop microbial, plant and animal biodiversity, strong-EMLS aims to render crop and livestock systems less sensitive to environmental hazards and change. In this ecological modernization form, production and health processes are considered closely interconnected and thus are jointly analyzed and managed to explain and control multifactorial diseases (Dumont et al. 2012). Furthermore, improving animal health reduces the risk of emissions of pharmaceutical residues into the environment.

Dynamics of agroecosystems can also be determined by the interaction between slow variables (e.g., soil organic matter, farm size, state of water resources, management agencies and social values) and fast variables (e.g., field management, water withdrawals, authorization to access resources). The former determines the conditions under which the latter occurs (Biggs et al. 2012). Weak-EMLS does not seek to manage slow biophysical and social variables locally. It is based on the use of exogenous inputs to meet requirements of the agroecosystem. The ecological system is artificialized, while the local social system is strongly embedded in the dominant supra-local agri-food chain. Slow variables at stake in weak-EMLS are mainly those in the entire agri-food chain, not those in the local social–ecological system. Conversely, the management principles involved in strong-EMLS aim to reach slow variable states to provide typical ecosystem services. For example, soil management seeks to develop high fertility (high soil organic matter and biological activity), while social-learning networks seek to improve individual and collective human capital and, accordingly, adaptive capacities.

## Analysis of examples of conventional and emergent livestock systems

### Dairy farm dynamics in Brittany

Most farming systems in Brittany (France) are dairy farms (17,000 out of 37,000 farms). Since the 1950s, local strong concentration of intensive livestock systems has induced strong economic and social development, but also public concern about human health hazards, food security, and environmental problems (Acosta-Alba et al. 2012). The French Government have set targets and specific regulations for decreasing environmental impacts based on scientific recommendations and national, European (e.g., EU Water Framework Directive), and global scales (e.g., Kyoto protocol) regulations and policies. Two main pathways corresponding to weak and strong-EMLS processes are observed.

The main and more developed path, supported by the dominant agricultural political movement, encourages farmers to optimize their systems by providing relevant tools such as planning and monitoring to manage grazing and farm-gate nutrient budgets to manage nitrogen. An alternative option is supported by farm networks called CIVAM that promote sustainable agriculture by implementing innovative ways to develop agriculture and rural activities as a part of sustainable territorial development. They promote and develop strategies to enhance the autonomy of farmers and their integration into local communities. They attempt to answer local questions from a global perspective about the functions and place of agriculture in society (RAD 2013). Farmers in these networks are more familiar with self-organization, reflexive analysis, and sharing experiences than most farmers involved in conventional dairy systems. Based on their personal experiences and histories, farmers can identify their sustainability priorities so as to improve their environment, solidarity, product quality, economic efficiency, and quality of life. Each farmer has a personal vision of the progress that he or she can accomplish. The agricultural innovation system that sustains these farmer networks is completely based on collective experimentation, organization, associated learning, and participation within the definition of collective objectives and expected specifications of production systems. For this, farmer networks organize local exchanges and training during economic and technical field trips. As for economic principles, farmers aim to be globally self-sufficient and locally interdependent. They seek to organize adapted governance into their adaptive farming systems and networks. However, since farm size is small, most CIVAM farmers specialize in dairy production. In addition to these principles, they contract for production specifications, including 75 % of forage resources coming from grasslands, <50 kg/ha of synthetic N fertilizer applied to grasslands, no bare soil in winter, rotation length of at least 4 years, only a small area in silage maize, and no plastic film used to grow maize. These specifications fundamentally seek to develop soil fertility (slow variables).

Assessing classical criteria for economic and environmental sustainability of these conventional livestock systems (in weak-EMLS) and CIVAM one (in strong-EMLS), crops and grasslands are more diversified in CIVAM farms (Table 3). Milk production per cow for CIVAM farms is lower, but economic results are higher due to lower costs of mechanization and industrial inputs. However, land required per cow is higher, and even more so per kg of milk produced. Clear differences are found in the number of pesticide applications, but differences in GHG emissions are small. Clear advantages for the environment appear for CIVAM farms only when assuming C sequestration by their large areas of semipermanent grasslands (Le Rohellec and Mouchet 2008; Le Rohellec et al. 2011).

For farmers involved in CIVAM networks, we recover the features of strong-EMLS: Owing to their limited use of purchased inputs to be self-sufficient, they search for autonomy in decision making, through developing their own technical reference framework, and thus can also contribute to alternative development pathways of rural territories (Coquil et al. 2014).

**Table 3** Comparison of conventional dairy farms and "sustainable dairy farm network" (CIVAM, a type of weak-EMLS) in Brittany (France)

| Domain | Criteria | CIVAM | Conventional |
|---|---|---|---|
| Structure | Agricultural land (ha) | 64 | 71 |
| | Animal unit (dairy cows) | 75 (49) | 96 (48) |
| Land use and management | Stocking rate (number of animal units/ha) | 1.28 | 1.61 |
| | Land use in percentage (grassland/maize/crops) | 69/12/19 | 58/21/21 |
| | Maize for silage (% of forage area) | 12 | 37 |
| | Hedge (ml/ha) | >150 linear meter/ha | No obligation |
| Economy | Inputs (euros/ha) | 100 | 240 |
| | Milk/cow (kg) | 5,749 | 6,636 |
| | Food cost (euros/1,000 l) | 78 | 120 |
| | Mechanization cost (euros/ha) | 400 | 500 |
| | Farm incomes (euros) | 134,718 | 157,309 |
| | Gross operating profit (euros) | 53,365 | 42,291 |
| Environment | Pesticide treatment frequency for maize[a] | 0.83–1.24 | 1.66 |
| | GHG emissions ($CH_4$, $CO_2$, $N_2O$ (kg eq $CO_2$/1,000 l)[b] | 1,100 | 1,100 |
| | Net GHG emissions (kg eq $CO_2$/1,000 l) | 874 | 1,018 |

[a] Number of applications with standard approved dosages

[b] Less $CH_4$ emissions for conventional farms; more C sequestered for CIVAM farms due to grasslands and hedges

## Position of well-known livestock systems in the weak to strong ecological modernization continuum

### *Organic agriculture: the example of beef farms*

Organic farming, which excludes the use of synthetic fertilizers, pesticides (herbicides, insecticides, and fungicides), livestock antibiotics, food additives, and GMO, is considered as one form of sustainable agriculture (Francis 2009). General ecological principles promoted in organic farming correspond to some of those that underpin strong-EMLS (e.g., crop diversity, development of legumes, animal health). However, due to the diversity of farmer viewpoints, two types of organic farmer organizations coexist: those supporting weak-EMLS and those supporting strong-EMLS (Francis 2009). The former are often organized as a subsector of the conventional agri-food chain. They correspond to "industrial organic production." The latter are generally organized in alternative networks that defend a new model of agriculture and agri-food system (e.g., based on local and short agri-food chains). In general terms, in their recent review, Gomiero et al. (2011) found that energy consumption and GHG emissions were lowest for organic versus conventional dairy farms in Europe, regardless of the functional unit of measure (per ha or per kg of milk). These authors pointed out that multi-criteria analysis based on key indicators is essential, because some systems may have an advantage for one criterion (e.g., fewer $CH_4$ emissions for conventional livestock systems), but a disadvantage for another (e.g., nutrient losses). However, being based on contractual obligations for inputs but not results, organic farming does not explore all the possibilities offered by the agroecological principles of the strong-EMLS. To bridge the productivity gap between organic and conventional agricultures, experts involved in organic agriculture recently suggested promoting "ecofunctional intensification," defined as stimulating more knowledge and using more intensively biological regulations (Niggli et al. 2008), both of which similar to the principles of strong-EMLS.

Comparison of productive, environmental, and economic performances of organic versus conventional specialized suckler cattle farms in France showed the former have lower meat production (by −18 to −37 %/ha), but also lower GHG emissions per ha (and per kg of animal live weight depending on system intensification) when taking C sequestration into account (Veysset et al. 2010). Operational costs of organic beef farms decreased due to a decrease in inputs (−9 to −52 %), while organic farm income decreased an average of approximately 20 % (Veysset et al. 2010).

In USA, alternative beef-production systems (e.g., organic, grass fed) offer consumers and producers alternatives to conventional beef production, but their production costs are usually higher (Matthews and Johnonson 2013). These beef systems have different properties (e.g., resource and other input use, GHG emissions, animal welfare, processing and food safety/security concerns) that may appeal to various consumers. In their analysis, Matthews and Johnonson (2013) emphasized that the trade-offs associated with each system can influence their attractiveness to consumers. For example, grass-based systems can produce a better fatty acid profile for meat and accordingly human health properties, while incentives for livestock systems in marginal lands can increase GHG emissions per unit of product.

### *What about integrated crop–livestock systems?*

The number of mixed crop–livestock farming systems, in which some of the crops are sold, has greatly declined in Europe and North America since the Second World War. However, integration of crops and livestock at the farm level, as already mentioned, is expected to provide many advantages (Wilkins 2008). Currently, mixed-farming systems are concentrated in less favorable areas where soil heterogeneity lead farmers to grow forage crops and grasslands. In this context, the environmental and economic performances of such systems are usually greater than those of specialized farms (Ryschawy et al. 2012). However, in specialized crop or livestock regions, many authors claim that, given the economic context, area-wide crop–livestock integration can be more successful than only farm-level integration (Moraine et al. 2014; Entz and Thiessen Martens 2009). Area-wide integration of crops and livestock (i.e., at the local level) can be an option to deal with a range of environmental and economic issues (e.g., nutrient surplus, water shortage, and low forage self-sufficiency of livestock farms) or challenges (e.g., decreasing industrial inputs of crop farms). It is based on exchanges of forage, grain, by-products, and manure between specialized crop and livestock farms and can be implemented through weak- or strong-EMLS. For weak-EMLS, it may consist of common facilities for producing energy from crop residues as well as manure, straw, or grain exchanges. It requires the proximity of crop and livestock production or the dehydration and exchange of products to limit the economic cost and environmental impacts of transport (Bell and Moore 2012). For strong-EMLS, it can occur by introducing legumes in rotations of specialized cash crop farms to be sold as grain or forage. This increases fertility and, if well distributed in the landscape, may favor biological regulations. Both of these ecosystem services could allow industrial inputs used in crop farms to be decreased while providing fodder for livestock farms (Sanderson et al. 2013). More broadly, crop and livestock integration at different spatial and temporal levels can constitute an ultimate form of strong-EMLS when designed to enhance a large set of ecosystem services (Lovell et al. 2010; Francis and Porter 2011; Moraine et al. 2014). However, when organized at the local/landscape level, it must organize local governance that promotes collective learning, experimentation and participation.

## Concluding remarks

Focusing on livestock systems at the local level and their land-use dimensions, we described and assessed the sustainability of two archetypal forms of these systems: weak and strong ecological modernization, which represent two archetypal extremes of a continuum. To manage the sustainability of these two types of livestock systems, we first assess their environmental, economic, and social performances and then their resilience by analyzing their governance and related properties. In weak-EMLS, reducing negative impacts of livestock systems on the environment, the main objective of the ecological modernization, is achieved by increasing input-use efficiency and waste recycling, while strong-EMLS, in addition to these principles, seeks to develop ecosystem services based on biodiversity. Our sustainability assessment demonstrates that one ecological modernization form might have advantages for certain criteria (e.g., fewer $CH_4$ emissions for weak-EMLS), but disadvantages for others (e.g., nutrient losses). Resilience is based on different properties. For weak-EMLS, it depends on the entire agri-food chain and its ability to provide technological and economical solutions that help livestock systems manage changes. In contrast, resilience of strong-EMLS is determined by characteristics of the local governance of agriculture, its levels of biophysical and social diversity and connectivity, and the way slow variables are managed.

In Western countries, organic agriculture can contribute to strong-EMLS. However, since it is based on contractual obligations for inputs but not results, it can fail to fully exploit ecological and socioeconomic principles that ground strong-EMLS. Crop and livestock integration can constitute an ultimate form of strong-EMLS when designed to enhance a large set of ecosystems and based on area-wide integration.

Assessing sustainability and resilience of the many existing and developing livestock systems in different geographical areas within a country can help politicians adapt their policies to meet their objectives. For example, in Europe, it can help in choosing a balance between direct payments to farmers for conditional observance of environmentally friendly practices and return payments that compensate additional costs and income losses when implementing agroecological practices that go beyond standard good farming practices. It can also help evaluate the advantages and disadvantages of conservation easements (i.e., for long-term ecosystem services) or market credits (e.g., for C sequestration). Furthermore, it can help advisors identify which skills and tools to develop according to the ecological modernization form they want to initiate. To meet this end, politicians and advisors must appreciate that the more pronounced forms of weak-EMLS have strong path dependency when encountering change. As Sutherland et al. (2012) demonstrate, this may limit their ability to deal with radically new environmental norms and market conditions.

**Acknowledgments** This paper has benefited of discussions that occurred in three projects: O2LA (Locally Adapted Organisms and Organizations; ANR-09-STRA-09) and TATABOX (Territorial Agroecological Transition in Action: a tool-BOX for designing and implementing a territorial agroecological system transition in agriculture; ANR-13-AGRO-0006), both funded by the French National Agency for Research, and CANTOGETHER (Crops and ANimals TOGETHER, FP7, Grant Agreement No. 289328), funded by the European Commission's Seventh Framework Programme (Food, Agriculture and Fisheries, Biotechnology).

## References

Acosta-Alba I, Lopéz-Ridaura S, van der Werf HM, Leterme P, Corson MS (2012) Exploring sustainable farming scenarios at a regional scale: an application to dairy farms in Brittany. J Clean Prod 28:160–167. doi:10.1016/j.jclepro.2011.11.061

Altieri MA, Nicholls CI (2004) Biodiversity and pest management in agroecosystems. Haworth Press, New York

Altieri MA, Funes-Monzote FR, Petersen P (2011) Agroecologically efficient agricultural systems for smallholder farmers: contributions to food sovereignty. Agron Sustain Dev 32:1–13. doi:10.1007/s13593-011-0065-6

Anderies JM, Folke C, Walker B, Ostrom E (2013) Aligning key concepts for global change policy: robustness, resilience, and sustainability. Ecol Soc 18(2):8

Anderson DM, Fredrickson EL, Estell RE (2012) Managing livestock using animal behavior: mixed-species stocking and flerds. Animal 6:1339–1349. doi:10.1017/S175173111200016X

Asai M, Langer V, Frederiksen P, Jacobsen BH (2014) Livestock farmer perceptions of successful collaborative arrangements for manure exchange: a study in Denmark. Agric Syst. doi:10.1016/j.agsy.2014.03.007

Bell LW, Moore AD (2012) Integrated crop–livestock systems in Australian agriculture: trends, drivers and implications. Agric Syst 111:1–12. doi:10.1016/j.agsy.2012.04.003

Biggs R, Schlüter M, Biggs D, Bohensky EL, BurnSilver S, Cundill G, Dakos V, Daw TM, Evans LS, Kotschy K, Leitch AM, Meek C, Quinlan A, Raudsepp-Hearne A, Robards MD, Schoon ML, Schultz L, West PC (2012) Toward principles for enhancing the resilience of ecosystem services. Annu Rev Environ Resour 37:421–448

Cabell JF, Oelofse M (2012) An indicator framework for assessing agroecosystem resilience. Ecol Soc 17(1):18

Coquil X, Béguin P, Dedieu B (2014) Transition to self-sufficient mixed crop–dairy farming systems. Renew Agric Food Syst. doi:10.1017/S1742170513000458

Coulon J, Delacroix-Buchet A, Martin B, Pirisi A (2004) Relationships between ruminant management and sensory characteristics of cheeses: a review. Le Lait 84:221–241. doi:10.1051/lait

Darnhofer I, Moller H, Fairweather J (2010a) Farm resilience for sustainable food production: a conceptual framework. Int J Agric Sustain 8:186–198

Darnhofer I, Bellon S, Dedieu B, Milestad R (2010b) Adaptiveness to enhance the sustainability of farming systems. A review. Agric For Sustain Dev 30:545–555. doi:10.1051/agro/2009053

Dewhurst RJ, Shingfield KJ, Lee MRF, Scollan ND (2006) Increasing the concentrations of beneficial polyunsaturated fatty acids in milk produced by dairy cows in high-forage systems. Anim Feed Sci Technol 131:168–206. doi:10.1016/j.anifeedsci.2006.04.016

Doré T, Makowski D, Malézieux E, Munier-Jolain N, Tchamitchian M, Tittonell P (2011) Facing up to the paradigm of ecological intensification in agronomy: revisiting methods, concepts and knowledge. Eur J Agron 34:197–210. doi:10.1016/j.eja.2011.02.006

Doreau M, Martin C, Popova M, Morgavi DP (2011) Leviers d'action pour réduire la production de méthane entérique par les ruminants. Productions Animales 24:461–474

Dumont B, Fortun-Lamothe L, Jouven M, Thomas M, Tichit M (2012) Prospects from agroecology and industrial ecology for animal production in the 21st century. Animal 1028–1043. doi:10.1017/S1751731112002418

Duru M, Farès M, Thérond O (2014) Un cadre conceptuel pour penser maintenant (et organiser demain), la transition agroécologique de l'agriculture dans les territoires (in French). A conceptual framework for thinking now (and organising tomorrow) the agroecological transition at the level of the territory Cahiers Agricultures 23:84–97

Entz MH, Thiessen Martens JR (2009) Organic crop–livestock systems. In: Francis CA (ed) Organic farming: the ecological system. ASA-CSSA-SSSA Book & Multimedia, Madison, pp 69–84

Eviner VT, Hawkes CV (2008) Embracing variability in the application of plant–soil interactions to the restoration of communities and ecosystems. Restor Ecol 16:713–729. doi:10.1111/j.1526-100X.2008.00482.x

Ewert F, van Ittersum MK, Heckelei T, Therond O, Bezlepkina I, Andersen A (2011) Scale changes and model linking methods for integrated assessment of agri-environmental systems. Agric Ecosyst Environ 142:6–17. doi:10.1016/j.agee.2011.05.016

FAO (2006) Livestock's long shadow. FAO collection: environmental issues and options. FAO, Rome, 390 p

Figuière C, Metereau R (2012) At the crossroads of industrial ecology and Syal. Advance the sustainability of a localized rural development. Communication au XXVIII journées de l'ATM, Orléans, 11–13 juin

Folke C, Carpenter S, Elmqvist T, Gunderson L, Holling CS, Walker B (2002) Resilience and sustainable development: building adaptive capacity in a world of transformations. Ambio 31:437–440

Francis C (2009) Education in organic farming and food systems. In: Francis CA (ed) Organic farming: the ecological system. American Society of Agronomy, Madison, Wisconsin pp 283–300

Francis CA, Porter P (2011) Ecology in sustainable agriculture practices and systems. Crit Rev Plant Sci 30:64–73. doi:10.1080/07352689.2011.554353

Franzluebbers AJ, Stuedemann J (2013) Crop and cattle production responses to tillage and cover crop management in an integrated crop–livestock system in the southeastern USA. Eur J Agron. doi:10.1016/j.eja.2013.05.009

Gebbers R, Adamchuk VI (2010) Precision agriculture and food security. Science (New York, NY) 327:828–831. doi:10.1126/science.1183899

Geels F (2002) Technological transitions as evolutionary reconfiguration processes: a multi-level persepective and a case-study. Res Policy 31:1257–1274

Gilbert CL, Morgan CW (2010) Food price volatility. Philos Trans R Soc B Biol Sci 365:3023–3034. doi:10.1098/rstb.2010.0139

Glasser F, Ferlay A, Chilliard Y (2008) Oilseed lipid supplements and fatty acid composition of cow milk: a meta-analysis. J Dairy Sci 91:4687–4703. doi:10.3168/jds.2008-0987

Gliessman SR (2006) Animals in agroecosystems. In: Agroecology: the ecology of sustainable food systems, 2nd edn. CRC Press, Boca Raton, pp 269–285

Gomiero T, Pimentel D, Paoletti MG (2011) Environmental impact of different agricultural management practices: conventional vs. organic agriculture. Crit Rev Plant Sci 30:95–124. doi:10.1080/07352689.2011.554355

Hendrickson JR, Hanson JD, Tanaka DL, Sassenrath G (2008) Principles of integrated agricultural systems: introduction to processes and definition. Renew Agric Food Syst 23:265–271. doi:10.1017/S1742170507001718

Hodgson J (1985) The significance of sward characteristics in the management of temperate sown pastures, vol 15. In: Proceedings of the XV international grassland congress, Kyoto, Japan, pp 63–66

Holt-Giménez E, Altieri MA (2012) Agroecology, food sovereignty and the new green revolution. J Sustain Agric 37:90–102. doi:10.1080/10440046.2012.716388

Hooper DU, Chapin FS III, Ewel JJ, Hector A, Inchausti P, Lavorel S, Lawton JH, Lodge DM, Loreau M, Naeem S, Schmid B, Setälä H, Symstad AJ, Vandermeer J, Wardle DA (2005) Effects of biodiversity on ecosystem functioning: a consensus of current knowledge. Ecol Monogr 75:3–35

Horlings LG, Marsden TK (2011) Towards the real green revolution? Exploring the conceptual dimensions of a new ecological modernisation of agriculture that could "feed the world". Glob Environ Chang 21:441–452. doi:10.1016/j.gloenvcha.2011.01.004

Ingram J (2008) Agronomist–farmer knowledge encounters: an analysis of knowledge exchange in the context of best management practices in England. Agric Hum Values 25:405–418. doi:10.1007/s10460-008-9134-0

Jackson L, van Noordwijk M, Bengtsson J, Foster W, Lipper L, Pulleman M, Said M, Snaddon J, Vodouhe R (2010) Biodiversity and agricultural sustainagility: from assessment to adaptive management. Curr Opin Environ Sustain 80–87. doi:10.1016/j.cosust.2010.02.007

Janzen HH (2011) What place for livestock on a re-greening earth? Anim Feed Sci Technol 166–167:783–796. doi:10.1016/j.anifeedsci.2011.04.055

Jiggins J, Roling N (2000) Adaptive management: potential and limitations for ecological governance. Int J Agric Resour Gov Ecol 1:28–42

Kajikawa Y (2008) Research core and framework of sustainability science. Sustain Sci 3:215–239. doi:10.1007/s11625-008-0053-1

Kirschenmann F (2010) Alternative agriculture in an energy- and resource-depleting future. Renew Agric Food Syst 25:85–89

Klerkx L, Van Mierlo B, Leeuwis C (2012) Evolution of systems approaches to agricultural innovation: concepts, analysis and interventions. In: Darnhofer I, Gibbon D, Dedieu B (eds) Farming systems research into the 21st century: the new dynamic. Springer, Dordrecht, pp 459–485

Knickel K, Brunori G, Rand S (2009) Towards a better conceptual framework for innovation processes in agriculture and rural development: from linear models to systemic approaches. J Agric Educ Ext 15:131–146

Kremen C, Iles A, Bacon C (2012) Diversified farming systems: an agroecological systems-based. Ecol Soc 17(4):44

Kuisma M, Kahiluoto H, Havukainen J, Lehtonen E, Luoranen M, Myllymaa T, Grönroos J, Horttanaine M (2012) Understanding biorefining efficiency—the case of agrifood waste. Bioresour Technol 135:588–597. doi:10.1016/j.biortech.2012.11.038

Lamarque P, Tappeiner U, Turner C, Steinbacher M, Bardgett RD, Szukics U, Schermer M, Lavorel S (2011) Stakeholder perceptions of grassland ecosystem services in relation to knowledge on soil fertility and biodiversity. Reg Environ Chang 791–804. doi:10.1007/s10113-011-0214-0

Lamine C (2011) Transition pathways towards a robust ecologization of agriculture and the need for system redesign. Cases from organic farming and IPM. J Rural Stud 27:209–219. doi:10.1016/j.jrurstud.2011.02.001

Le Rohellec C, Mouchet C (2008) Efficacité économique de systèmes laitiers herbagers en agriculture durable (RAD): une comparaison avec le RICA. Fourrages 193:107–113

Le Rohellec V, Mouchet C, Boutin M, Brault J (2011) Analyse de l'efficacité économique et environnementale des systèmes laitiers herbagers économes et autonomes 2007–2010. Rencontre Recherche Ruminants, Paris, pp 297–300

Leat P, Lamprinopoulou C, Revoredo-Giha C, KupiecTeahan B (2011) Agri-food supply chains and sustainability-related issues: evidence from across the Scottish agri-food economy. In: 85th annual conference of the Agricultural Economics Society, 25 pp

Lebacq T, Baret PV, Stilmant D (2012) Sustainability indicators for livestock farming. A review. Agron Sustain Dev 33:327–331. doi:10.1007/s13593-012-0121-x

Lemaire G, Hodgson J, Chabbi A (2011) Introduction: food security and environmental impacts—challenge for grassland sciences. In Grassland productivity and ecosystem services. CABI, Wallingford, pp xiii–xvii, Hardback, 312 pp

Lemaire G, Franzluebbers A, Carvalho PCDF, Dedieu B (2014) Integrated crop–livestock systems: strategies to achieve synergy between agricultural production and environmental quality. Agric Ecosyst Environ 190:4–8. doi:10.1016/j.agee.2013.08.009

Lovell TS, DeSantis S, Nathan CA, Breton Olson M, Méndez VE, Kominami HC, Erickson DL, Morris KS, Morris WB (2010) Integrating agroecology and landscape multifunctionality in Vermont: an evolving framework to evaluate the design of agroecosystems. Agric Syst 103:327–341. doi:10.1016/j.agsy.2010.03.003

Marsden T (2012) Towards a real sustainable agri-food security and food policy: beyond the ecological fallacies? Polit Q 83:139–145. doi:10.1111/j.1467-923X.2012.02242.x

Martens J, Thiessen R, Entz MH (2011) Integrating green manure and grazing systems: a review. Can J Plant Sci 91:811–824. doi:10.4141/CJPS10177

Matthews KH, Johnonson RJ (2013) Alternative beef production systems: issues and implications/LDPM-218-01. Economic Research Service/USDA. Alternative beef production systems: issues and implications/LDPM-218-01, 34 pp

Moraine M, Duru M, Nicholas P, Leterme P, Therond O (2014) Farming system design for innovative crop–livestock integration in Europe. Animal 1–14. doi:10.1017/S1751731114001189

Morris C, Winter M (1999) Integrated farming systems: the third way for European agriculture? Land Use Policy 16:193–205. doi:10.1016/S0264-8377(99)00020-4

Niggli U, Slabe A, Schmid O, Halberg N, Schlüter M (2008) Vision for an organic food and farming research agenda to 2025 organic knowledge for the future iFOAM Regional Group European Union (IFOAM EU Group) Technology Platform 'Organics', 45 pp

Power AG (2010) Ecosystem services and agriculture: tradeoffs and synergies. Philos Trans R Soc B Biol Sci 365:2959–2971. doi:10.1098/rstb.2010.0143

RAD (2013) (sustainable agriculture network) www.agriculture-durable.org/

Rains GC, Olson DM, Lewis WJ (2011) Redirecting technology to support sustainable farm management practices. Agric Syst 104:365–370. doi:10.1016/j.agsy.2010.12.008

Reganold JP, Andrews PK, Reeve JR, Carpenter-Boggs L, Schadt CW, Alldredge JR, Ross CF, Davies NM, Zhou J, El-Shemy HA (2010) Fruit and soil quality of organic and conventional strawberry agroecosystems. PLoS One 5(9):e12346

Ryschawy J, Choisis N, Choisis JP, Joannon A, Gibon A (2012) Mixed crop-livestock systems: an economic and environmental-friendly way of farming? Animal 6:1722–1730. doi:10.1017/S1751731112000675

Sanderson MA, Archer D, Hendrickson J, Kronberg S, Liebig M, Nichols K, Schmer M, Tanaka D, Aguilar D (2013) Diversification and ecosystem services for conservation agriculture: outcomes from pastures and integrated crop–livestock systems. Renew Agric Food Syst 1–16. doi:10.1017/S1742170512000312

Schiere JB, Darnhofer I, Duru M (2012) Dynamics in farming systems: of changes and choices. In: Darnhofer I, Gibbon D, Dedieu B (eds) Farming systems research into the 21st century: the new dynamic. Springer, Dordrecht, pp 339–365

Shennan C (2008) Biotic interactions, ecological knowledge and agriculture. Philos Trans R Soc B Biol Sci 363:717–739. doi:10.1098/rstb.2007.2180

Singh JS, Pandey VC, Singh DP (2011) Efficient soil microorganisms: a new dimension for sustainable agriculture and environmental development. Agric Ecosyst Environ 140:339–353. doi:10.1016/j.agee.2011.01.017

Sorathiya LM, Fulsoundar B, Tyagi KK (2014) Eco-friendly and modern methods of livestock waste recycling for enhancing farm profitability. Int J Recycl Org Waste Agric 3:50. doi:10.1007/s40093-014-0050-6

Sulc RM, Franzluebbers AJ (2013) Exploring integrated crop–livestock systems in different ecoregions of the United States. Eur J Agron. doi:10.1016/j.eja.2013.10.007

Sutherland LA, Burton RJF, Ingram J, Blackstock K, Slee B, Gotts N (2012) Triggering change: towards a conceptualisation of major change processes in farm decision-making. J Environ Manag 104:142–151. doi:10.1016/j.jenvman.2012.03.013

Tauseef SM, Premalatha M, Abbasi T, Abbasi S (2013) Methane capture from livestock manure. J Environ Manag 117:187–207. doi:10.1016/j.jenvman.2012.12.022

Ten Napel J, van der Veen AA, Oosting SJ, Groot Koerkamp PWG (2011) A conceptual approach to design livestock production systems for robustness to enhance sustainability. Livest Sci 139:150–160. doi:10.1016/j.livsci.2011.03.007

Tomich TP (2010a) Agroecology. Annu Rev Environ Resour 36:193–222

Tomich TP (2010b) Agroecology. Annu Rev Environ Resour 36:110301095711090. doi:10.1146/annurev-environ-012110-121302

Tripp R (2008) Agricultural change and low-input technology. In: Snapp S, Pound B (eds) Agricultural systems: agroecology and rural innovation for development. Elsevier, Amsterdam, pp 129–160

Tscharntke T, Klein AM, Kruess A, Steffan-Dewenter I, Thies C (2005) Landscape perspectives on agricultural intensification and biodiversity- ecosystem service management. Ecol Lett 8:857–874. doi:10.1111/j.1461-0248.2005.00782.x

Turner BL II (2010) Vulnerability and resilience: coalescing or paralleling approaches for sustainability science? Glob Environ Chang 20:570–576. doi:10.1016/j.gloenvcha.2010.07.003

Van Oudenhoven APE, Petz K, Alkemade R, Hein L, de Groot RS (2012) Framework for systematic indicator selection to assess effects of land management on ecosystem services. Ecol Indic 21:110–122. doi:10.1016/j.ecolind.2012.01.012

Vanclay F (2004) Social principles for agricultural extension to assist in the promotion of natural resource management. Aust J Exp Agric 44:213–223

Vanloqueren G, Baret PV (2009) How agricultural research systems shape a technological regime that develops genetic engineering but locks out agroecological innovations. Res Policy 38:971–983. doi:10.1016/j.respol.2009.02.008

Vermeulen SJ, Aggarwal PK, Ainslie A, Angelone C, Campbell BM, Challinir AJ, Hansen JW, Ingram JSI, Jarvis A, Kristjanson P, Lau C, Nelson GC, Thornton PK, Wollenberg E (2012) Options for support to agriculture and food security under climate change. Environ Sci Policy 15:136–144. doi:10.1016/j.envsci.2011.09.003

Veysset P, Lherm M, Bébin D (2010) Productive, environmental and economic performances assessments of organic and conventional suckler cattle farming systems. Org Agric 1:1–16. doi:10.1007/s13165-010-0001-0

Walker B, Holling CS, Carpenter SR, Kinzig A (2004) Resilience, adaptability and transformability in social–ecological systems. Ecol Soc 9(2):5

WCED (1987) Report of the World Commission on environment and development. NGO Committee on Education of the Conference of NGOs from United Nations web sites

Wilkins RJ (2008) Eco-efficient approaches to land management: a case for increased integration of crop and animal production systems. Philos Trans R Soc B Biol Sci 363:517–525. doi:10.1098/rstb.2007.2167

Williams BK (2011) Passive and active adaptive management: approaches and an example. J Environ Manag 92:1371–1378. doi:10.1016/j.jenvman.2010.10.039

Wilson G (2008) From "weak" to "strong" multifunctionality: conceptualising farm-level multifunctional transitional pathways. J Rural Stud 24:367–383. doi:10.1016/j.jrurstud.2007.12.010

Zhang W, Ricketts TH, Kremen C, Carney K, Swinton SM (2007) Ecosystem services and dis-services to agriculture. Ecol Econ 64:253–260. doi:10.1016/j.ecolecon.2007.02.024