Socioecological metabolism of livestock areas : an environmental accounting approach

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List of Abbreviations of variables used in analysis

Agrotourism	Proportion of farms practicing agrotourism
ASF	Animal Source Food
AWU	Annual Work Unit
Biodiv	Proportion of grassland birds in bird community
Depend ratio	Dependence ratio (purchased feed/ final livestock output)
EmpFarm	Workforce on livestock farms
EmpInd	Employees in livestock agrofood industry
Employ	Contribution of livestock sector to overall employment
FAS	Average farm size
FCR	Nitrogen Feed Conversion Ratio
Herb LU	Herbivore Livestock Units
Herb Meat MFA	Herbivore meat production per hectare of main fodder area (cattle, sheep, and goat meat)
Herb SR	Herbivore stocking rate
HNV	Area classified as High Nature Value
Landscape	Areas in heritage landscapes (grassland, specific areas, and trees)
LU	Livestock Units (cattle, sheep, goat, horse, pig, poultry)
MFA	Main Fodder Area
MFA:UAA	Share of main fodder area in utilised agricultural area
Milk MFA	Milk production per hectare of main fodder area (cow, sheep, and goat milk)
Mon LU	Monogastric Livestock Units
Mon SR	Monogastric stocking rate
Nb farms	Number of farms
NEE	Nitrogen Excretion Emissions
NSS	Nitrogen Self-Sufficiency
NSU	Nitrogen Surplus
NUE	Fodder Nitrogen Use Efficiency
Product	Number of quality-labelled animal products (SIQO)
Tractor dens	Tractor density
UAA	Utilised Agricultural Area
UAA:AWU	Labour productivity
UAA:DEP	Share of utilised agricultural area in the department
Water	Proportion of municipalities outside nitrate vulnerable zones

Definitions of key notions

Livestock sector: the set of terrestrial domestic species including cattle, sheep and goat, pig, poultry (chicken, turkey, duck and guineafowl).

Performance: in the context of livestock sustainability, performance refers to the ratio of output per unit input or environmental impact (e.g. kg meat . ha^{-1} or per kg CO_2 emitted) hence the proposed list of indicators: Animal source food, N Self-sufficiency, Fodder Nitrogen Use Efficiency and N Feed Conversion Ratio.

Environmental impact: the effects of anthropogenic activities on the natural environment, such as the use of resources, waste generation and emissions (Gallego-álvarez et al., 2014). We considered two proxies of environmental impacts: a local one (N Surplus), and a global one (N Excretion Emissions).

Metabolism: the concept of metabolism is adapted from biology to study the biophysical (material and energy) exchange relationships between societies and their natural environment (Erb, 2012).

Trajectories of intensification: consists on the different paths of change occurred during the intensification process of the livestock sector in the past century.

List of Publications

<u>Articles</u>

Domingues JP, Ryschawy J, Bonaudo T, Gabrielle, B and Tichit M (*in press*) Unravelling the physical, technological, and economic factors driving the intensification trajectories of livestock systems. Animal: An International Journal of Animal Bioscience

Domingues JP, Gameiro A, Bonaudo T, Gabrielle, B and Tichit M (*in prep*) Exploring synergies and trade-offs among performance and environmental impacts indicators in livestock areas

Domingues JP, Gameiro A, Bonaudo T, Gabrielle, B and Tichit M (*in prep*) How current social, environmental and cultural services provided by livestock are linked to past intensification trajectories?

Oral communications to international conferences

Domingues JP, Bonaudo T, Gabrielle, B and Tichit M (2015) Nitrogen conversion efficiency in French livestock production from 1938 to 2010. 66th Annual Meeting of the European Association of Animal Science, Warsaw, Poland. Book of abstracts.

Gameiro A, Tichit M, Gabrielle B, **Domingues JP**, Bonaudo T (2015) Trends of material flow accounts in the Brazilian livestock sector: insights and prospects for research development. In: Anais IV Simpósio de Sustentabilidade & Ciência Animal. Rio de Janeiro, Brazil.

Domingues JP, Gameiro A, Bonaudo T, Gabrielle, B and Tichit M (2016) Livestock farming system diversity and resource use efficiency. What the history tells for France? 67th Annual Meeting of the European Association of Animal Science, Belfast, North Ireland. Book of abstracts.

Bonaudo T, **Domingues JP**, Tichit M and Gameiro A (2016) Interest and limits of territorial metabolism methods for analyzing the flow of matter and energy in the livestock territories. 23rd Rencontres Recherches Ruminants. Paris, France.

Puillet L, Bonaudo T, **Domingues JP**, Jouven M, Pomeon T and Tichit M (2017) Analyzing the spatial variation of crop and livestock balance on a nation-wide gradient. 68th Annual Meeting of the European Association of Animal Science, Tallinn, Estonia. Book of abstracts.

Organization of the manuscript

This thesis is organized in two Parts.

- The Part A is a general presentation of the research carried out during the PhD training. It describes the scientific literature background, which leads to the statement of the goal, and of specific objectives formulated in the form of three research questions (Chapter I). Next, I present a general methodological aspect of the work (Chapter II). Chapter III summarizes the main results and brings basic interpretations. Chapter IV includes the general discussion, highlighting perspectives, implications and limitations brought by results.
- Part B is an appendix, formed of three scientific articles (Chapters V, Chapters VI, and Chapters VII). They contain specific elements of comparison and discussion in relation to the literature.

A. GENERAL PRESENTATION

I. INTRODUCTION

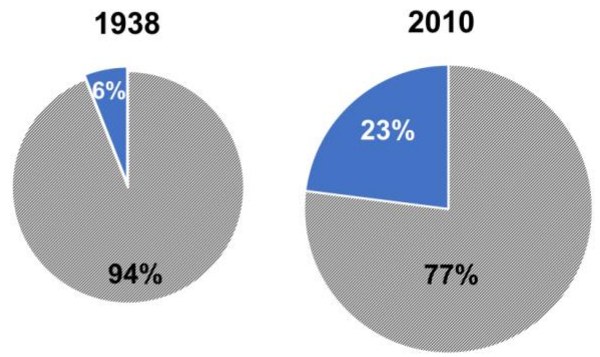
1. Intensification of livestock production

1.1. The link between livestock production, land and resource use

Past characteristics of livestock production were marked by the close link between animals and land. Global changes in the food production system have contributed to loosen this link (animals and land), and posed a threat to the sustainability of current production means (Herrero and Thornton, 2013). Until the past mid-century, livestock was kept as a source of food security, income, draft power, and insurance to farm households. It transformed on-farm grown human-inedible resources and food waste, into edible products, and provided organic fertilizer to crop cultivation. Mixed crop-livestock systems were predominant and regularly distributed in agricultural areas. They constituted a *sine qua non* of agricultural production. Farming did not rely much on external inputs, except for inputs from atmosphere, like in biological nitrogen fixation and deposition, and goods for the household consumption (Bonaudo et al., 2015). Livestock mainly transformed waste and fibers into human edible products, and manure had essential role on reestablishing soil fertility, and allowing crop production (Krausmann, 2004). With high resource recycling rates, nutrient cycles were mainly closed at farm level.

In the mid of the 20th century, the Green Revolution contributed to loosen the link between livestock and land. This development took place due to the Haber-Bosch process of ammonia synthesis from gaseous dinitrogen that allowed increased use of synthetic nitrogen fertilizers. Increasing mechanization fostered this trend, along with the use of other inputs, favored by the high amounts of subsidies granted to agriculture in developed countries (Galloway et al., 2008; Pretty and Bharucha, 2014). In addition, increased international trade, reflecting globalization moves towards free market agreements, have also contributed to the specialization of producing regions. Maintenance of soil fertility for crop production no longer depended on livestock manure. The nutrient connection between arable land and livestock was increasingly removed in many regions of the world. A progressive separation between arable crops, mostly cultivated in plains, and livestock farming in mountain areas therefore became apparent in many regions of the world (Lambin et al., 2001).

Because of the spatial segregation of crop and livestock production, the distances between areas of feed production and areas where livestock are grown have substantially increased (Billen et al., 2015). Livestock and crop production are not only separated at national level but at global level as well. Currently livestock is the major driver of the global trade of proteins– through high amounts of soybean sales, and the amount of nutrients recycled in farms has drastically reduced (Bouwman et al., 2005; Billen et al., 2014; Lassaletta et al., 2014). Industrial systems, such as for pigs and poultry, are no longer linked to a local land base for feed input sourcing (Naylor, 2005). Herrero et al. (2013) shows that industrial systems in developed countries uses ~78% of feed concentrates and the rest is used for dairy production and feedlot operations. EU countries currently produce sufficient energy feed crops but imports a high share of feed protein across the Atlantic. Imports of feed protein in France increased by 7 fold in the past century. In 1938 France imported 0.35 Tg of protein feed in the form of meal, barley, maize and rice, and in 2010 imports reached 2.38 Tg of protein, from which soybean meal accounted to 63% (**Figure I-1**).



	1938	2010
Total consumption (Tg)	6.00	10.12
- Local production	5.65	7.74
- Imports	0.35	2.38

Figure I-1. Livestock protein feed consumption and sourcing in France between 1938 and 2010. Grey colour for locally sourced protein feed, and blue for globally sourced. (Source: 1938, Commission de Modernisation de la Production Animale; 2010, Agreste).

1.2. Intensification and regional specialization of land use

Intensification can be seen as a process that increases land productivity by expanding input use per unit area, or as the set of possible combinations of labour-, capital-, and technology-related parameters that achieve a higher production per unit area (Shriar, 2000). Therefore, intensification can be measured by the quantity of production per area or per animal as well as by the quantity of inputs per unit area or animal or by a quantity of input per unit product (Herzog et al., 2006; Temme and Verburg, 2011; Teillard et al., 2012). Changes in land can be classified into two types: (a) changes in land cover that alter the biophysical characteristics of the land via the expansion or contraction of a given land use type, such as the encroachment of cultivated crops into permanent grassland areas, or (b) changes in land use intensity accompanied by changes in the levels of socioeconomic inputs to the land (e.g., labour, feed resources, or capital) and/or altered outputs per unit area and time, such as increased animal stocking rates (Erb, 2012).

During the second half of 20th century, with many actors playing in the competition for land, agricultural land use went through intensification to make a more efficient use of land and to decrease the share of food budget in household expenses. In many areas changes lead to specialization, characterized by large scale operations with a single/specific production objective. In Europe the process of regional specialization was fast and continuous, and occurred in many countries. In France and in the UK, extensive areas of grasslands, once dominated by herbivores, were converted to cropland (Potter and Lobley, 1996; Xiao et al., 2015). This trend gained momentum on the post-war period, with the setting of the Common Agricultural Policy (CAP), to guarantee food security and better conditions of rural population. The CAP goal was achieved with rising agricultural yields, also incentivized by good conditions of global markets. The gains (76%) in crop production in the past 50 years in Western European countries, were largely achieved thanks to increasing yields (72%), as the harvested areas remained nearly unchanged (**Figure I-2**).

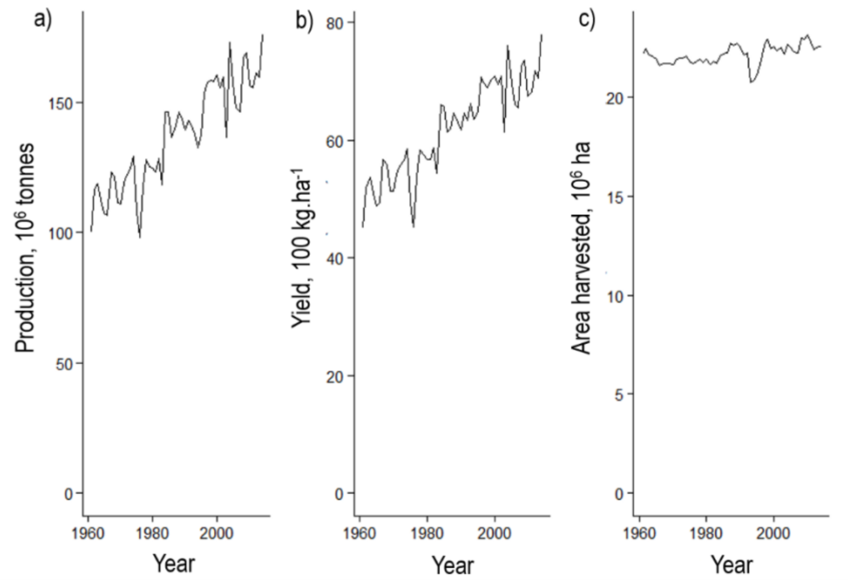


Figure I-2. Agricultural intensification in Western EU countries. a) crop production, b) yield, and c) area harvested. Countries: Benelux, Austria, France, German and Switzerland; crops: cereals, oil-protein crops and tubers. (Adapted from: Dross, 2016.)

In the case of France, the main determinants of specialization were linked to the agronomic potential (e.g. biophysical conditions and soil fertility), and structural factors, such as farm size (Peyraud et al., 2014). Workload availability on rural areas also played a role. At low levels of work availability and large farm size, crops were favored over livestock in the Paris basin. High levels of work availability fostered the development of intensive livestock systems in Brittany.

Areas that specialized in crop production share characteristics linked to a high productivity, high input of pesticides and fertilizers, reduced share of natural grasslands, increased mechanization and farm size, and low crop rotation (Stoate et al., 2001; Herzog et al., 2006; Le Féon et al., 2010). In France, between 1960 and 2010, gains in milk and meat yields (about threefold increase), allowed meeting local demand for food and feed, and even generated a surplus exported to other areas (Teillard d'Eyry, 2012).

Areas that specialized in livestock production display different patterns of intensification. Some areas evolved to high levels of animal performance thanks to developments in breeding, nutrition and animal health. High stocking rates contributed to increased output of livestock products. Other areas- where biophysical conditions did not favor intensive systems, have emphasized extensive production at low stocking rates and low product output per unit land. During the past fifty years, at global level, beef production more than doubled, and chicken meat production increased 10 fold (Thornton, 2010). In EU countries, livestock numbers grew considerably in the 1960s and 1970s, until the 1980s, when numbers started decreasing for cattle, stabilized for pig, and continued growing for poultry. In 2008, EU represented a share of 26%, 13%, 22%, 12% and 11% of the world's production of milk, beef, pork, poultry and eggs, respectively (Lesschen et al., 2011).

Areas that emphasized grazing were often located in marginal areas such as in the southern Europe and mountainous regions (Bernués et al., 2011). Because of biophysical conditions, these areas tend to adopt lower stocking rates and often have lower output per unit head and land. Areas with crop-mixed livestock systems, share production characteristics of crop and livestock production specialized areas. The reconnection of livestock with cropping systems allows higher productivity of land and better resource use efficiency (Bonaudo et al., 2014). These areas have intensive or extensive use of resources, and they currently provide about half of the world's food (Herrero et al., 2010).

1.3. Heterogeneous livestock production

The intensification process of agriculture influenced the development of livestock into heterogeneous types of production systems. Regions responded in diverse ways to drivers of intensification according to biophysical conditions and socioeconomic context. Livestock farming systems therefore operate at different levels of intensity, with diverse production objectives in varied agro-ecological zones (Herrero et al., 2015a).

The level of intensity of farming systems is the main determinant of animal productivity and the use of resources. High levels of production intensity are often associated with livestock raised at high densities with a relatively large fraction of grains in the diets. This pattern is observed in most countries of developed world and in some crop-livestock systems, allowing higher levels of feed-use efficiency (Herrero et al., 2013).

The agro-ecological zone influences the type of livestock system, and species that can be raised in one region. It is defined by varied combinations of soil, landform and climatic characteristics that determines crops, fodders and animal species adapted to that specific context. Semi-arid areas yield lower quality feed resources, such as shrubs and low digestibility forages, and are suitable for small-ruminants production in pastoral systems. Humid and temperate areas provide conditions to high yield crops and fodder cultivation, allowing the development of intensive and mixed livestock systems based on large ruminants.

The production objective, such as milk, meat and eggs, is conditioned to a large extent by the agro-ecological zone. Most areas emphasizing ruminant production, whether for milk or meat purpose, have a strong link to local fodder resources. In Europe more intensive systems rely on local production of forage and cereals but often depend on protein imports to meet feed requirements.

The combination of different levels of production intensity, with varied production objectives in diverse agro-ecological zones, results in highly heterogeneous patterns of livestock farming systems around the world (**Figure I-3**). Agro-ecological zones influences the availability and quality of feed resources, thus the potential productivity that can be achieved (Van Ittersum et al., 2013).

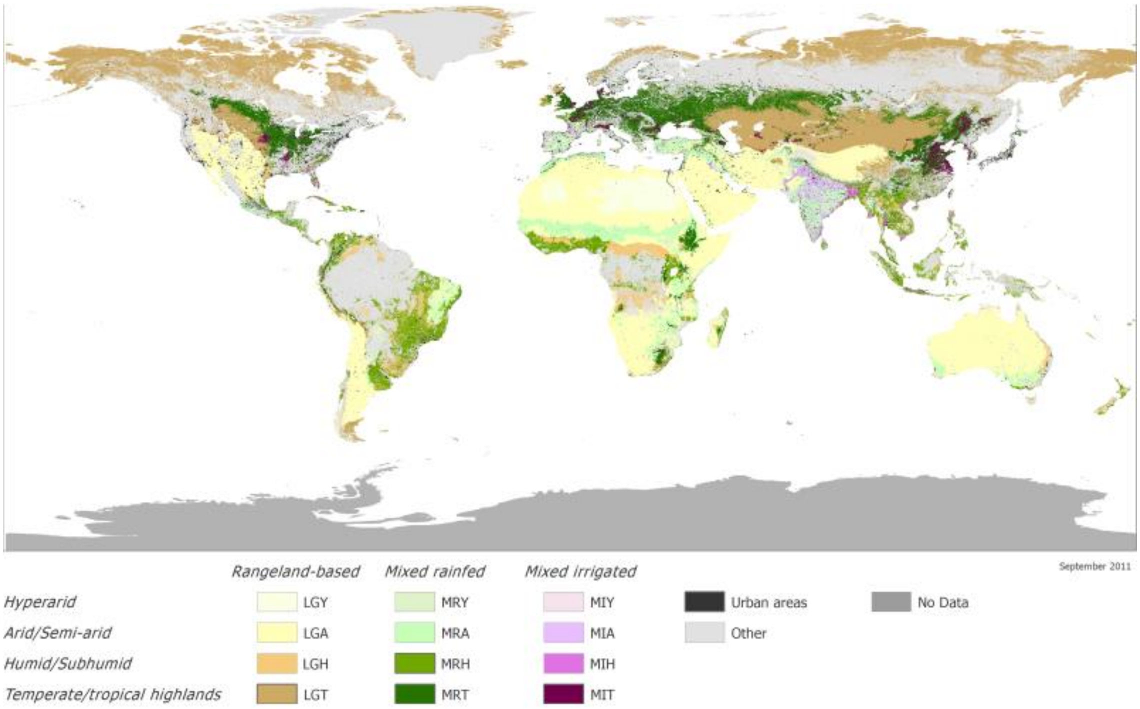


Figure I-3. Global Livestock Production Systems. Source: (Robinson et al., 2011)

Heterogeneous patterns of ruminant livestock farming systems have been described by IDELE, 2012. Figure **I-4** illustrates the diversity of livestock systems in France, grouped into thirteen types in this classification. They encompass plains and mountainous regions, specialized and mixed systems, and varied levels of production intensity and objective of production. An important feature of this typology is that it accounts for the areas with and without alternative to livestock.

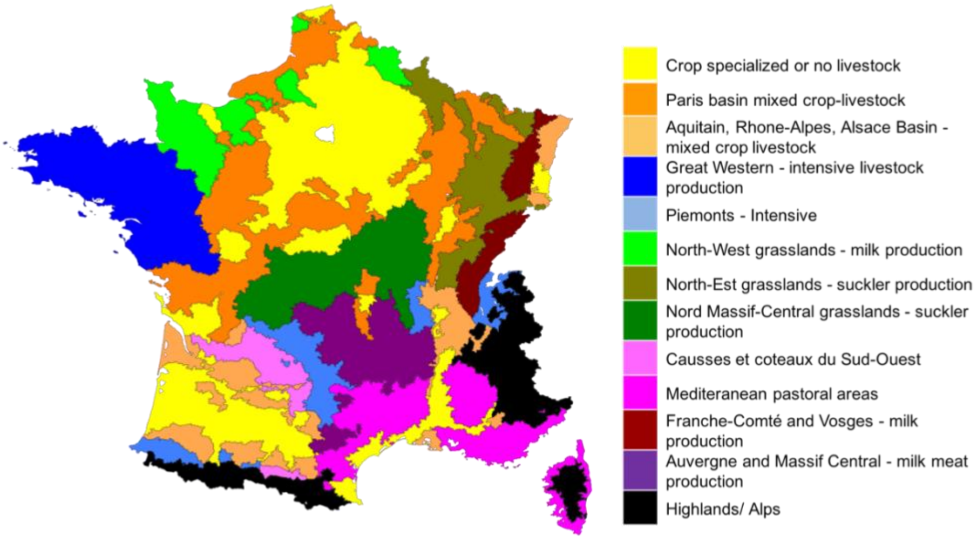


Figure I-4. Zoning of the main ruminant livestock areas in France. Zoning is based upon criteria of agro-ecological zone, production objective, level of intensity and land use. Source: IDELE, 2012.

1.4. Efficiency and environmental impacts of livestock production

Efficiency can be defined as the level of output per unit of input, and can be measured taking different perspectives, namely land, water, nutrients, energy, or biological diversity (Keating et al., 2010). Its use in agricultural science emphasizes achieving more agricultural output, regarding quality and quantity, with less input of land, water, nutrients, labour or capital. Measuring and seeking improved efficiency of production is essential to achieve/maintain food security, though livestock provision of protein, energy and micro-nutrients to human nutrition. The environmental performance of a system can be defined as the effects of anthropogenic activities on the natural environment, such as the use of resources, waste generation and emissions (Gallego-álvarez et al., 2014).

Because of the existing heterogeneity in livestock systems, production in different regions is achieved at varied levels of efficiency and environmental impacts.

Different livestock production systems can have different efficiencies and contribute to varied levels of environmental impacts (de Vries and de Boer, 2010; Lesschen et al., 2011). **Figure I-5** illustrates varied levels of environmental impact within and between species, in terms of global warming potential (CO_2-e.kg^{-1}), which suggests –among many reasons, different efficiencies of converting feed resources and large variety of production systems. The livestock footprint is a concern that raised the attention of many scientists and many assessments have been conducted with the aim to improve environmental impact (Van Der Werf and Petit, 2002).

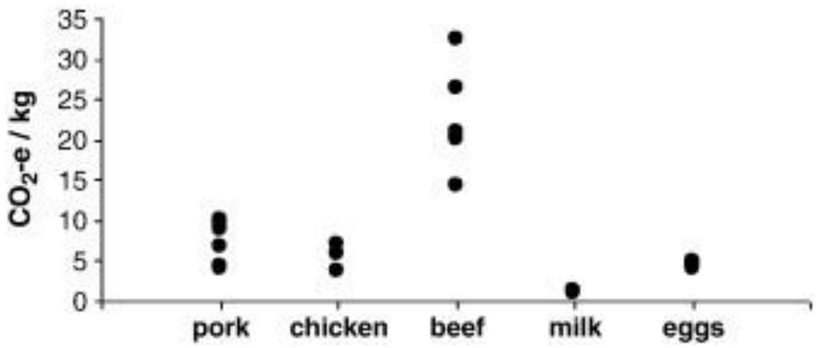


Figure I-5. Global warming potential for livestock products , in CO_2-e expressed per kg of product. Extracted from: Vries and Boer (2010)

Another way of measuring environmental impact of livestock consist on studying the relationship between systems' inputs and outputs. Rotz et al. (2005) reported a general non-linear relationship between input and output of human edible products, whereas a linear relationship is observed between inputs and losses. **Figure I-6** illustrates that beyond a certain input level, there are no gains in productivity, but losses increase, because of inherent biological limits of crops and animals to convert inputs into edible outputs (Hutchings et al., 2011).

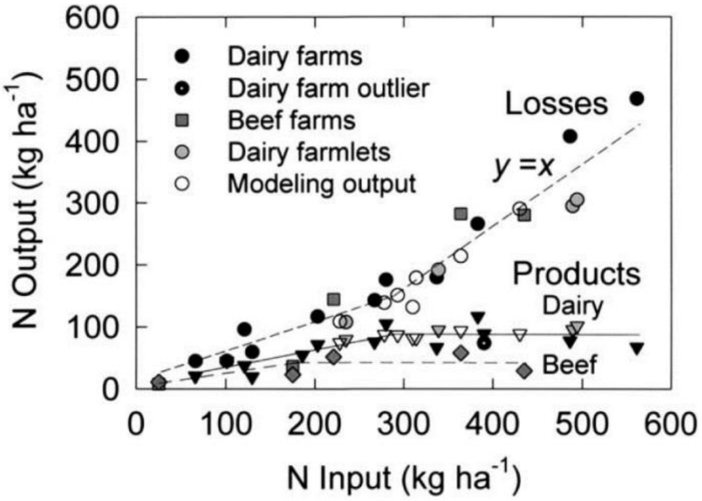


Figure I-6. Relationship between total annual N input and N output. N output as products (milk, meat and crops – shown as triangles) and as losses (volatilization, denitrification, run-off, leaching and transfer to unproductive areas – shown as circles) in dairy and beef production systems that involve some grazing. Extracted from Rotz et al. (2005).

Assessing the efficiency of feed conversion provides insights on productivity perspectives as well as on environmental quality, as low resource-use efficiency is linked to high impacts (Herrero et al., 2015a). Additionally, measuring efficiency is useful to explore the ability of heterogeneous systems in converting different feed resources into human edible products (Wilkinson, 2011). Although low efficiency of feed conversion is often associated with higher environmental impacts, a single metric cannot be sufficient as a surrogate of a system overall sustainability. Issues on low efficiency are manifold, and can be related to water use, land use, biomass harvest and greenhouse gas emissions for instance (Gerber et al., 2015). The efficiency to which livestock transform resources into edible products can be translated into varied levels of performance and impacts. In this view, Van Zanten et al. (2016) proposed the land use ratio. It measures the maximum amount of human-digestible protein (HDP) derived from food crops on all land used to cultivate feed required to produce 1 kg animal source food (ASF) over the amount of HDP in that 1 kg ASF. It provides insights on efficiency of animal feed conversion, land productivity and suitability to grow crops as well as the ability of land and livestock to produce human-edible protein.

The assessment of livestock efficiency can become more complex when scaling up from animal, to farm, and to regional levels. Analysis at higher aggregated levels can result in outcomes that were not visible at lower levels and also reveal new interactions that can present opposite trends across levels. Most of prior efforts to improve efficiency were achieved through animal-centred approaches, with attention mainly focused on animal performance and linked to gains in feed conversion efficiency (Iribarren et al., 2011; Zehetmeier et al., 2012; Shortall and Barnes, 2013; Mu et al., 2017). These studies have not payed attention to how gains in efficiency were affecting the surrounding environment, the watershed or region for instance. Several recent studies demonstrated the need to consider efficiency beyond the animal level to account for the complementarity between improving yields at animal and crop levels, as well as to trade-offs of changing scales/levels (Mottet et al. 2017; Godinot et al. 2014; cite also Billen Lassaleta here). Godinot et al. (2014) developed the 'system nitrogen efficiency' (SyNE) to improve estimation of N efficiency at farm level. For a given land productivity level (kg N output.ha^{-1}), they found that gains in SyNE reduced potential N losses. But changing productivity levels, in cases of intensification would result in higher losses, and in cases of extensification would reduce losses.

At regional level, Le Noë *et al.* (2017) studied nitrogen, phosphorus and carbon flows of agro-food systems. They highlighted the role of specialisation and intensification on losses in cropland and grasslands. However, the way they formalize the livestock compartment, which is used for closing flows, fails to account for the large heterogeneity of livestock species reared with varied practices in relation to land and resources.

The above remarks call for more detailed efficiency concepts, which precisely address the land-based resources use and, their ecological and economic opportunity costs at different levels (Herrero et al., 2015b). In light of achieving sustainable livestock production, it is essential to capitalize on multi-metrics to account for the contribution of livestock to food supply, land use and impacts.

2. Assessing the sustainability of livestock production

2.1. Measuring sustainability

2.1.1. Dimensions and scales of sustainability

According to Loos et al. (2014) the most accepted definition of sustainability is associated to the idea of 'meeting present needs without compromising the ability of future generations to meet their own needs', as proposed by (Keeble, 1988). The authors also highlight the consensus on the necessity to balance anthropogenic development with environmental quality. Sustainability as a broad concept is often characterized by three dimensions: economic, environmental and social. Some authors give new names to dimensions, without changing initial meaning, and sometimes propose new dimensions, as suggested by Makkar and Ankers (2014), with the ethical dimension on the sustainability of livestock feed. The consensus inherent to the concept generally implies an equal balance among the multiple dimensions of sustainability.

In the livestock sciences, more work is needed to achieve this balance. Lebacq et al. (2013) describe indicators used to study livestock related issues and found an imbalance among sustainability dimensions. They found that research tends to focus on the environmental dimension, with lower attention paid to economic and even lower to social aspects. The imbalance is explained by the strong emphasis laid by stakeholders (e.g., civil society, researchers, and agricultural policy makers) on environmental issues because they already cover large and complex impact categories. Within the economic dimension there is also an imbalance. There is significant information on profitability, as monetary data is usually recorded in farm accountancy databases. Fewer attention is paid to indicators regarding the farm self-sufficiency and diversification. Social dimension is more difficult to assess as it often depends on qualitative appraisals. It is also challenging to measure because of differences in perception of social sustainability between farmers and other societal groups (van Calker et al., 2007).

Besides seeking a balance among sustainability dimensions, it is also essential to carefully balance the indicators that compose each dimension. A multi-metric set of indicators allows to better exploring complex characteristics related to the functioning of livestock systems. An empirical example is provided by Ross et al. (2017), who illustrate environmental sustainability of dairy systems. The authors showed how the functional unit to which impacts were referenced influences sustainability. Dairy systems show the highest efficiency when emissions are referred to unit products, and lowest efficiency when referred to on-farm land. This highlights the need to account for impacts attributed to both unit produce (e.g. kg of fat-and-protein-corrected milk) as well as to unit of land area (e.g. farmed hectare).

In addition to the need of equal balance among and within sustainability dimensions, the question of scales is similarly essential. Thornton and Herrero (2001) emphasized that information from higher hierarchical levels is necessary to provide a more complete description of the system under study. Cross-scales accounts are necessary, as interactions can display different trends at different scales. This is account is demonstrated by Soteriades et al. (2016) in the assessment of eco-efficiency of dairy farms in France. The authors found that although increasing milk yield per cow improves environmental performance at the cow-level, this does not hold at the farm level, because of increasing dependence on external feed resources.

These considerations stress the need of a multi-criteria approach for assessing livestock sustainability, and giving equal balance to indicators among and within dimensions, and at different levels. Likewise, the selection of metrics covering the different components of systems, land/plant/animal, is required as well as a broad range of indicators of environmental impacts.

2.1.2. Insufficient attention to trade-offs between sustainability indicators

Trade-offs occur when increase of one indicator results in decrease of another (Rodríguez et al., 2006). Although this is a generic definition of trade-offs, it is important to note that trade-offs cannot be limited to negative correlation between two indicators. Trade-off analysis requires considering the desirable trend of indicators. For environmental impacts, the desirable trend is a decreasing one, whereas for performance the desirable trend is an increasing one. Because of the nature of the intensification process, increased production is often associated to increased negative impacts thus leading to trade-offs between performance and impacts. Herrero et al. (2009) highlighted keys aspects for analyzing the link between livestock, and society and the environment (**Table I-1**). Future changes are very likely to result in trade-offs between food security, poverty, equity, environmental sustainability and economic development. The authors also expect trade-offs between breeding for increased efficiency of resource use, domino effects on performance (e.g. production and fertility and environmental impacts (Knaus, 2009, 2015). Finally, the authors underlined the role and the need of whole-system and life-cycle approaches for unravelling these complexities.

Table I-1 presents some key questions selected in line with trade-offs relevant to livestock systems in temperate countries. It presents trade-offs questions concerning sustainability dimensions, making clear the interrelation among them, and allows treating different types of trade-offs across systems.

Table I-1. Key trade-off questions about livestock, society and the environment per type of system. Adapted from (Herrero et al., 2009)

General

- Can we meet the demand for livestock products in an environmentally sustainable way?
- Will livestock systems intensification lead to more sustainable livestock benefits for society?
- Can the limits to sustainable intensification be adequately defined and indicators for measuring it developed and monitored in livestock systems?

Pastoral and agro-pastoral systems

- Pastoralists could participate of the economic benefits of livestock/wildlife co-existence but human population density, agricultural intensification are increasing rangeland fragmentation. Can this be reversed?

Mixed crop–livestock systems

- Intensifying the diets of ruminants can decrease methane produced per unit of output, but can this be done without increasing demand for grains?
- Intensification of production may increase food production in parts of the developing world but it could also erode the diversity of animal and plant genetic resources as more productive animals and plants are sought. What is the best compromise?
- Mixed systems are gaining significant research interest but will these systems remain as productive and economically viable as their more industrialized counterparts?

Industrial systems

- Large efficiency of conversion of output/unit of feed in the productivity of monogastrics is possible but dependence on concentrates will increases demands for feed grains that in turn fuel deforestation in the neotropics. What are alternative options?
- Systems in North America and Europe are heavily subsidized to maintain certain environmental and landscape benefits but at the same time creating demand for feed (grains) and resources elsewhere thus fueling deforestation. Is this sustainable? How do we account for these indirect effects?

Lemaire et al. (2014) advocated that trade-offs could be softened if more focus is placed on mixed crop-livestock systems. The authors suggested that trade-offs arise because of the loss of diversity (integration of crop and livestock) and that the reconnection of crop-fodder to livestock is the solution for achieving sustainable production. They point to options to soften trade-offs between food production and environment conservation at landscape or regional level, thanks to the complementarity between crops and grasslands.

As trade-offs are commonplace, no single indicator alone should be used to represent the environmental impact of livestock. Ross et al. (2017) assess emissions intensity of dairy production systems and identify trade-offs between land and production efficiencies. They show that improvement in emissions intensity using one functional unit (energy-corrected milk yield) may be accompanied by deterioration using another functional unit (on-farm land use). Thus, the choice of the set of indicators is a key step for a meaningful assessment of sustainability issues. Furthermore, several works made available comprehensive knowledge on individual metrics to assess livestock impacts on the environment. Herrero et al. (2015a) emphasized the need to move beyond single metrics/dimension, and move to multi-metric frameworks with indicators encompassing socioeconomic and cultural aspects, human nutrition, and a variety of environmental impacts.

2.1.3. Insufficient attention to social and cultural dimensions

The assessment of sustainability in livestock farming systems in the scientific literature is more focused on environmental and economic aspects (Ryschawy et al., 2017; Beudou et al., 2017). Fewer attention is placed on the socio-cultural dimension. The socio-cultural dimension is more difficult to measure and often depends on qualitative assessments (Lebacq et al., 2013). Equal balance over environment, economic and social dimensions is needed and more attention on socio-cultural aspects is vital to equalize this balance. Recent studies acknowledge the lack of attention to this dimension, and propose an account in different ways to help closing this knowledge gap.

The concept of ecosystem services (ES) emerged on the earlier 90s and gained momentum in 2005 with the Millennium Ecosystem Assessment (MEA, 2005). It emphasizes the benefits that ecosystems provide to humans. ES are classified in four types: provisioning, supporting, regulating and cultural (MEA, 2005). Oteros-Rozas et al. (2014) focused on the socio-cultural valuation of ecosystem services (ES) in a transhumance network, and explored human attitudes and perception regarding it. They showed the interest and potential of this account in revealing the importance of traditional agrarian landscapes for the delivery of a diverse flow of ES. Rodríguez-Ortega et al. (2014) review the application of the ES framework to pasture-based livestock farming systems in EU. The authors found farmers gave more importance to regulating and provisioning ES, whereas non-farmers gave more importance to cultural ES, showing different concerns. Ripoll-Bosch et al. (2013) evaluated, from a life cycle perspective, the environmental impacts of sheep farming systems at different degree of intensification. The authors considered impacts referred per unit of lamb output in a first moment, and then valued the conservation of biodiversity and the cultural landscape. They found contrasted trends in impacts of the two systems upon these two criteria, and suggest cultural aspects should also be integrated into the evaluation framework as it better highlights the multi-functionality of pasture based systems.

The account of social dimension is essential not only in terms of livestock contribution to society - as it covers the 'hidden benefits' provided by livestock, but also as a means to facilitate the transition from 'unsustainable' farming systems toward more sustainable ones (Ryschawy et al., 2013). Understanding the social value linked to livestock production is capital to designing strategies to steer systems in the 'desired/desirable' direction. Beudou et al. (2017) provided a first vision on how two French territories share different perceptions on cultural and territorial vitality services. This allowed the authors to identify and prioritize different services, such as territorial vitality and cultural identity, which could function as obstacles or levers towards the agroecological transition of livestock.

2.2. Frameworks for assessing sustainability

2.2.1. Product and land based approaches

As mentioned in previous sub-section 2.1.1, most of the attention of sustainability assessments is placed on the environmental dimension. Various approaches can be used to study the environmental impact of livestock production. Two approaches are described here, the product and land based approaches. A brief view of two approaches is shown in the following paragraphs.

Table I-2 and a schematic representation is illustrated in **Figure I-7**. Life cycle assessment and material flow accounting are the two approaches that provide a more holistic view of systems. They thus require large amount of data. They have different scope, which is dependent on the objectives, which may vary according to the goal of the analysis. Advantages and limitations exist for both, and are discussed in the following paragraphs.

Table I-2. Overview of two approaches used to assess impacts in livestock production. (Extracted from: Gerber et al., 2014)

Approach	Definition	Scale	Environmental impacts	Data requirements
Life cycle assessment	Environmental impact per unit of product.	Supply chain	Quantified per unit of output.	+++
Material flow analysis	Map of quantified material flows in the system.	System	Characterizes fluxes of environmental pressure.	+++

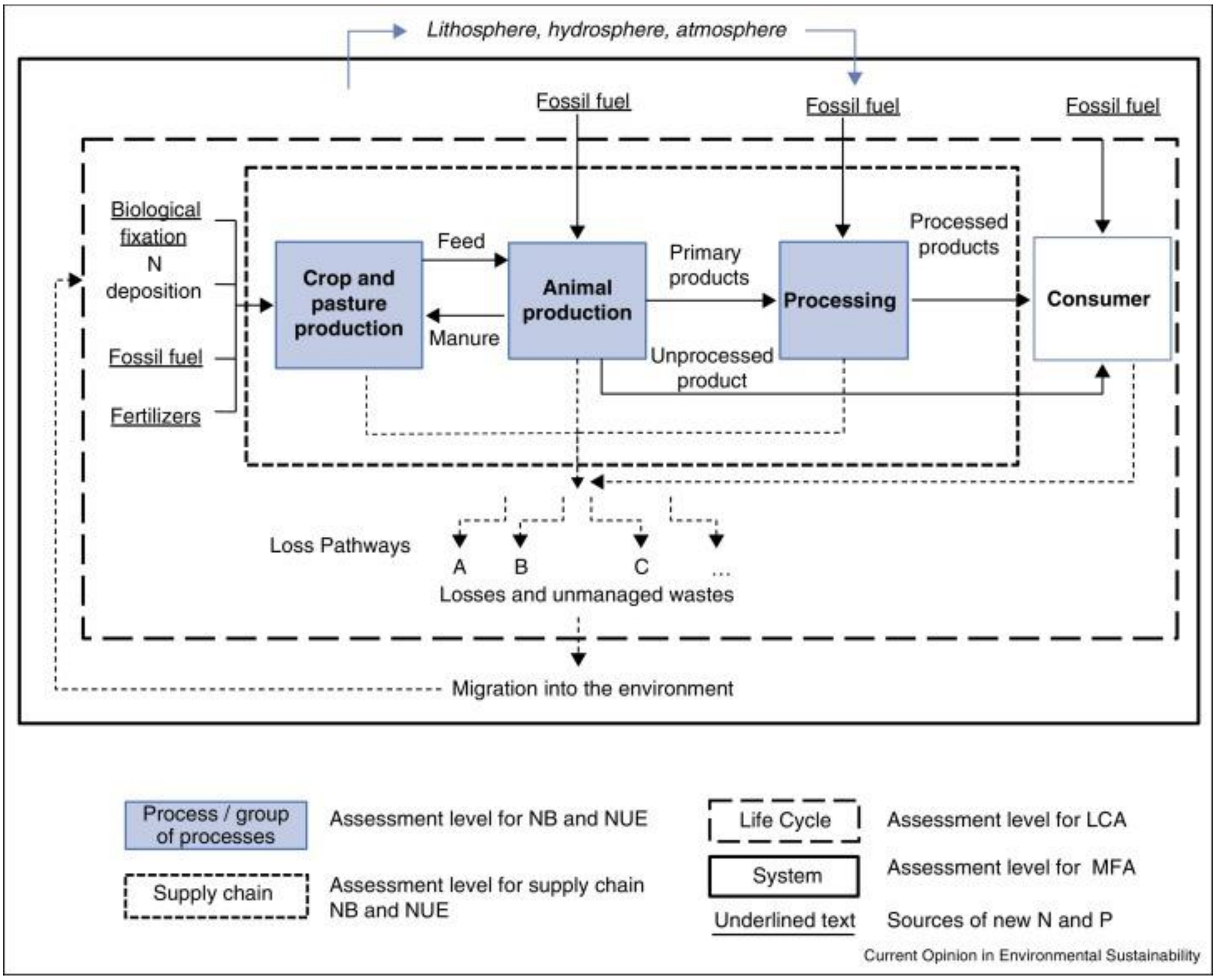


Figure I-7. Schematic representation of frameworks for the assessment of nutrient use in livestock systems. Extracted from: (Gerber et al., 2014)

Life cycle analysis (LCA) is an approach used to evaluate the environmental impacts during the entire life cycle of a product (de Vries and de Boer, 2010). LCA was created in the 70s to assess industrial processes, and in the end of the 90s it was adapted to agriculture (Van Der Werf and Petit, 2002). It provided a new way of measuring the human impact to the environment, taking an accounting perspective within a system thinking approach. LCA allows the identification of the main pollution sources along the chain, from accounts of production of farm inputs, to end-product at farm gate. It also evaluates possible structural changes of farms or farming practices. Many studies published on environmental impact are based on LCA methodology. LCA can provide different impact category indicators, such as global warming or acidification potential, land use, energy use, eco toxicity and eutrophication (de Boer, 2003).

Product-based approaches are often based on life cycle assessment (LCA) and expresses resource use and impacts per unit of product, e.g. greenhouse gas emissions per kilogram milk (Halberg et al., 2005). Schader et al. (2014) pointed to some common trends in LCA's results related to dilution effects. In many situations, the main conclusion is that increasing output yields (e.g. milk and meat) compensates additional environmental impacts of feed production. Yet, readers can often conclude that the use of concentrates is environmental-friendly. However, this single-supply-chain perspective does not account for the absolute boundaries of natural resource availability from a regional perspective. Therefore, Schader et al. (2014) suggested that in order to draw conclusions on large scales, a mass-balance approach is of capital interest. Yet, the mass-balance approach enables to connect processes (e.g. food/feed/livestock production) to the reality of physical flows and the land capacity to support plant and animal production.

As product-based and land-based approaches often yields different results, the limitations needs to be considered in the interpretation of results. This is even more important if the objective of assessment is to compare farming systems with different degrees of productivity (Halberg et al., 2005). For instance, extensive farming systems generally have lower yields and emissions per hectare, however they have higher emissions per unit product compared with more intensive systems. An objective way to deal with this question is to combine land-based for local/regional environment impacts, and product-based for global impacts.

2.2.2. The metabolism thinking

The mass balance approach is at the core of the metabolism thinking. The metabolism thinking provide a complementary approach to LCA. It enables analysis at large scales (regional, national, global), allowing the connection of livestock to land resources, which is a key aspect for sustainability assessment.

Fischer-Kowalski et al. (2011) provide a comprehensive description of the material flow accounting (MFA) from the beginning of the concept until the present developments. The MFA thinking has its origins in 1969 as an attempt to have a better view of production and consumption processes, keeping in mind the law of the conservation of mass. It has since then evolved from an initial idea to solve the ‘materials balance problem’ to a consolidated approach, now used word-wide as analytical tool for understanding resource use.

Adriaanse et al. (1997) described the MFA approach in a physical basis in order to characterize the sustainability of industrial economies. They highlighted the approach advantages to “*systematically track the physical flows of natural resources through extraction, production, fabrication, use and recycling, and final disposal, accounting for all losses along the way*”. A key aspect is that the MFA approach has being developed with the goal to relate the use of natural resources to the capacity of natural systems to provide materials and to absorb losses. Driving from this perspective, the approach has attracted attention among researches studying biogeochemical flows in agro-ecosystems.

Applications of the approach gained more importance on accounts of nutrient flows, as recent capital studies highlight the role of anthropogenic developments on the disruption of natural cycles (Galloway et al., 2003; Bouwman et al., 2009). In view of recent environmental issues, the MFA presents an added-value because it allows identifying environmental pressures in connection with the direct/indirect driving process and consequential outcome. From a temporal perspective, it also allows understanding metabolic transitions – with insights into changes in the scale and nature of material use over time – and linking it to associated socioeconomic processes (Krausmann et al., 2008).

Erb (2012) highlighted the usefulness of the metabolism approach: *i)* to understand changes in land-use intensity; *ii)* to unfold mechanisms and drivers of land use; *iii)* to design strategies aiming to achieve sustainability goals. Erb et al. (2013) designed a socioecological framework allowing to integrate the three dimensions of land-use, namely input and output intensity, the benefits and also the unintended outcomes of land based production systems. This framework allows to accounting for both synergies and trade-offs of livestock production, the provision of socioeconomic and environmental services, as well as the negative impacts associated to land-use change, such as alterations of biogeochemical cycles of nutrients and climate change (**Figure I-8**).

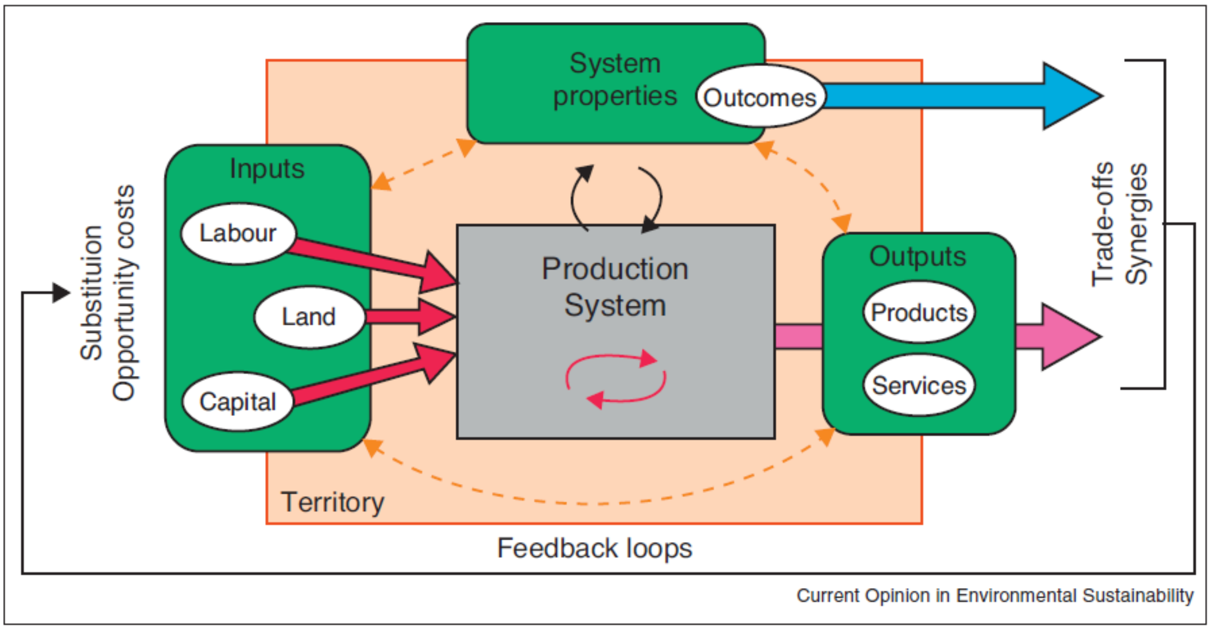


Figure I-8. The conceptual framework of land-use intensity. (Adapted from Erb et al., 2013)

An example on the use of the MFA approach is available on **Figure I-9**. Billen et al. (2014) applied the metabolism thinking to studying nitrogen use on agro-food systems, covering global production, consumption and trade. The implementation allowed identifying regional patterns of nitrogen use, and major factors determining the performance of agro-food systems world-wide.

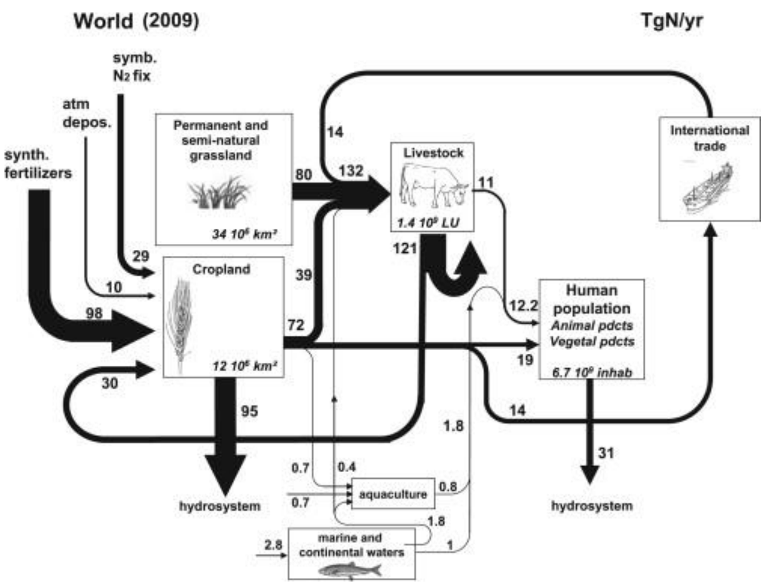


Figure I-9. Representation of the global agro-food system in 2009. Nitrogen flow exchanges among processes: land-based, livestock and human population Source: (Billen et al., 2014).

Despite recent developments and improvements on methods concerning the MFA, the full potential of the approach is still underused, especially on studies related to livestock production. First, there is a predominance of macro/larger-scales analysis, and a lack of considerations in terms of livestock heterogeneity (i.e. species and resource use). Second, approaches often consider the human compartment as the single driver of biomass flows, and use the livestock compartment to balance out the systems' flows. This later limits the scope of the MFA approach as it does not enable to explore changes in the functioning of livestock systems.

The fact that livestock is considered a major driver of land and resources use, asks for a more accountable position in any land-based approaches (Geist and Lambin, 2002; Havlík et al., 2013). Livestock is a direct driver through the occupation of a large extent of grasslands, roughly 40% of global agricultural area. Livestock is an indirect driver through the use of another 10% of global agricultural area to produce feed crops, which represents 40% of the global arable land (Mottet et al., 2017). In the first instance, above mentioned global analyses provided invaluable knowledge and the milestones of the metabolism thinking. Now, it is necessary to move beyond the methodological simplifications once used to achieve global coverage (i.e. use of livestock for closing flows balance). It is essential to account for the heterogeneity of livestock systems, management practices, resource-use efficiencies, and mitigation potentials (Herrero et al., 2013).

3. Research Questions

The development of the livestock sector in the past century undergone a strong intensification process. The spatial differentiation of intensification may have contributed to the heterogeneity of livestock farming systems existing today. Different degrees of disconnection between livestock and land, in diverse farming systems, have resulted in varied levels of performance and impacts. To date, a lot of research effort has been directed at measuring environmental impact and economic performance of livestock production. Insufficient attention has been paid to the three dimensions of sustainability, to tradeoffs among dimensions and to existing livestock heterogeneities. An approach that enables connecting livestock to land and resources, at regional level, could bring novel insights on the place/role of livestock in use and transformation of resources. The general goal of this PhD thesis is:

To develop a holistic assessment of livestock areas using multi-metric indicators encompassing positive and negative contributions

The steps we take to achieve the goal:

Research question 1:

What are the most influencing factors of the process of intensification?

We created a typology to study the most relevant processes of change in the livestock sector in France since 1938. It was based on indicators describing physical, technological, and socio-economic factors. Our hypothesis was that the current spatial heterogeneity of livestock production is the result of distinct intensification trajectories.

Research question 2:

How different configurations of livestock areas influence performance and impacts across areas?

We developed a material flow accounting of nitrogen and use it to derive indicators of performance and impact at the resolution of departments. For 48 departements we study the spatial differentiation of trade-offs and synergies. Our hypothesis was that the differences in overall performance were driven by the balance between herbivores and monogastrics, and land use types.

Research question 3:

To what extent social, environmental and cultural services provided by livestock are linked to past intensification trajectories?

We created a typology to study the influence of past intensification on the current provision of social, environmental and cultural services by the livestock sector. Our hypothesis was that distinct intensification trajectories resulted in contrasted level of service provisioning at present.

II. GENERAL APPROACH

1. Case study

1.1. Why France

France is an interesting case study, because the French livestock sector strongly influences land use, occupying roughly 50% of the utilised agricultural area (UAA) in 2010 for fodder production and 14% for feed concentrate (Agreste, 2015). In terms of reared species, level of intensity, combination of factors of production (land, labour, and capital) and edaphoclimatic conditions, France has one of the European Union (EU) most diversified livestock sector. **Figure II-1** shows a typology of livestock production areas in Europe, and provides a classification of six types of areas varying from grasslands to crop dominate areas and from low to high livestock densities. All six are present in France. Thus, French livestock production areas serve as representative examples of the variety observed throughout Europe.

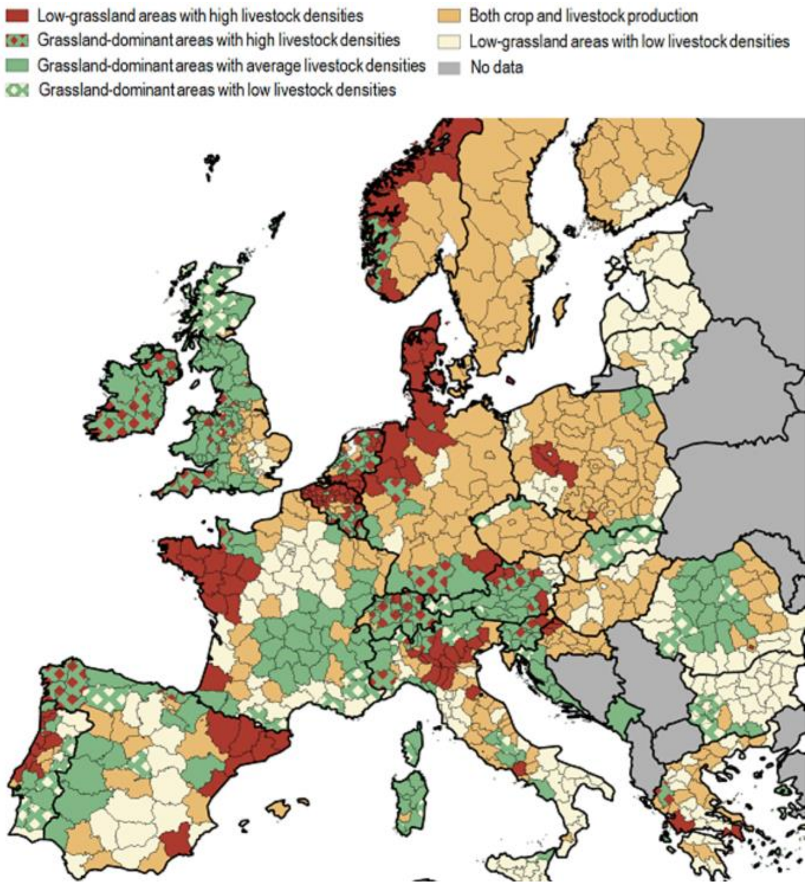


Figure II-1. Typology of European livestock production areas (Source: Dumont et al. 2016).

1.2. Variables, time frame and spatial extent of analysis

Our three research questions required data compilation from diverse sources, a range of years and details, with a summary provided below:

- The area extent involved the whole country of France, with starting year 1938 and final year 2010.
- The variables used were described at the Territorial Units for Statistic level 3 (NUTS3 level), which corresponds to the French administrative entity called department.
- We accounted for crop, fodder, and livestock productions.

A synthesis of main features data-wise of each research question is provided below and recapitulated in **Table II-1**.

The first research question consisted on building a typology based on data describing socioeconomic, land use, and production characteristics. It covered 88 French departments, and seven years from 1938 to 2010.

The second research question focused on 48 French departments corresponding to the two main intensification trajectories identified on the first step. They gathered the main livestock areas and both extremes of the livestock intensification gradient. We quantified nitrogen flows related to livestock production for these 48 departments and computed indicators to assess their performance and impacts on the year 2010.

The third research question consisted on studying how a heterogeneous process of intensification resulted in diverse patterns of services provisioning at present. This analysis was focused on 60 departments having a significant level of livestock specialization.

Table II-1. Research questions outline: variables, time frame and spatial extent.

Research Question	Variables	Time frame	Spatial extent
1	Herbivore stocking rate	1938	88 NUTS3
	Monogastric stocking rate	1955	
	Meat productivity	1970	
	Milk productivity	1980	
	Share of utilised agricultural area	1988	
	Share of main fodder area	2000	
	Average farm size	2010	
	Labour productivity		
	Dependence ratio		
	Tractor density		
2	Nitrogen use efficiency	2010	48 NUTS3
	Feed convertion ratio		
	Animal source food		
	Nitrogen self-sufficiency		
	Nitrogen surplus		
	Nitrogen emissions		
3	Variables of case study 1 plus:	2010	60 NUTS3
	Employment in livestock farms		
	Employment in livestock agrofood industry		
	Contribution of livestock to employment		
	High Nature Value of landscape		
	Conservation of biodiversity		
	Water quality		
	Heritage landscapes		
	Agrotourism		
	Heritage animal products		

1.3. Data series, sources, and indicator selection

We used a large French livestock database available at the department level (Cavailhes et al., 1987), which provided the unique opportunity to trace changes in the departments over long periods (years 1938, 1955, 1970, and 1980). A collation of more recent data from the agricultural census allowed us to extend the series through to 1988, 2000 and 2010 (Agreste, 2015). This extensive period ranging from 1938 to 2010 made it possible to capture major changes related to farm modernisation and the CAP that occurred after WWII. The initial database (Cavailhes et al. 1987) did not provide any estimates of pig or poultry production, which were mainly associated with subsistence farming from 1938 until the

1970s, reflecting the reduced importance of trade and the lack of statistics regarding the production of monogastrics. Nevertheless, we considered data on the population of monogastrics, which were available since 1938.

Data were organized into three categories of variables: land use, socioeconomic, and livestock (**Table II-2**). The land use variables characterised the relative importance of fodder and arable land in the departments and were used to rank the lands according to the area allocated to fodder production for livestock. The socioeconomic variables involved labour workforce availability, mechanisation, farm size, and dependence on purchased feed. The livestock variables included population size and the stocking rate of herbivores (cattle, sheep, goats, and horses) or monogastrics (pigs and poultry), as well as herbivore meat and milk production. Data were assembled in a table (D), composed of v continuous variables (v = 10), d departments (d = 88) and y years (y = 7), so that each data point in D refers to a specific variable v, for year y and department d.

Table II-2. Variables considered in the analysis of trajectories.

Variable name	Abbreviation	Units
Livestock variables		
Livestock Units (cattle, sheep, goat, horse, pig, poultry)[1]	LU	LU
Herbivore Livestock Units	Herb LU	LU
Monogastric Livestock Units	Mon LU	LU
Herbivore stocking rate*	Herb SR	$LU.ha^{-1}$
Monogastric stocking rate*	Mon SR	$LU.ha^{-1}$
Herbivore meat production per main fodder area (cattle, sheep, and goat meat)*	Herb Meat MFA	$kg.ha^{-1}$
Milk production per main fodder area (cow, sheep, and goat milk)*	Milk MFA	$litres.ha^{-1}$
Land-use variables		
Utilised Agricultural Area	UAA	ha
Main Fodder Area	MFA	ha
Share of utilised agricultural area in the department*	UAA:DEP	-
Share of main fodder area in utilised agricultural area *	MFA:UAA	-
Socioeconomic variables		
Number of farms	Nb farms	-
Annual Work Unit[2]	AWU	AWU
Average farm size*	FAS	ha
Labour productivity*	UAA:AWU	$ha.AWU^{-1}$
Dependence ratio (purchased feed/ final livestock output)*	Depend ratio	-
Tractor density*	Tractor dens	$Tractors.ha^{-1}$

*Variables used in the Principal Component Analysis for research question 1. 1) Complying with Eurostat standard. 2) Before 1970 accounts only for male workers, but after 1980 accounts for the work performed by one person on an agricultural holding on a full-time basis.

2. Building a typology to study the intensification process

2.1. Methodological approach main feature

To study changes in livestock production over time, we utilised the within-class principal component analysis (PCA) developed by Dolédec and Chessel, (1987), which was designed to analyse the spatiotemporal changes in a given system and had previously been used to analyse changes in livestock farms (García-Martínez et al., 2009; Ryschawy et al., 2013). The within-class PCA method enables a distinction between the effects due to structural factors and the effects of time in change trajectories. A strength of trajectory analyses is to emphasise changes over a long period, rather than the analysis of a select instant in time, which could yield a simplified view of reality. Our analysis was dynamic, and included a diverse set of variables (technical, land use, and socioeconomic), which enabled us to capture important factors in the process of livestock production intensification. A detailed description of the data compilation and the statistical analysis is provided in the following section.

2.2. Statistical analysis of trajectories

The statistical analysis of the department trajectories included four major steps: principal component analysis (PCA), between-class analysis, within-class analysis, and a hierarchical cluster analysis (HCA).

First, PCA was performed on all data in table D to reduce the number of variables while maintaining the largest possible variance (80.9%). We used the Kaiser criterion to select four factors with eigenvalues >1, which resulted in the generation of a new table (DN). Second, a between-class analysis and a within-class analysis were performed on table DN. The between-class analysis enabled the identification of the variables that had undergone the greatest change between the years, removing the effects of time, whereas the within-class analysis enabled the identification of the variables that had undergone similar changes within the years, which accounted for the effects of time. Third, we analyzed the results of the within-class analysis using the Kaiser criterion to select three factors that explained 73.6% of the total variance between the departments' trajectories. Fourth, a HCA based on the squared Euclidean distance and Ward's aggregation method was performed on these three factors and the typology of departments was generated based on their change trajectories. The Tukey's test was performed on HCA results to compare trajectories means for significant statistic difference at $P < 0,05$. All statistical procedures, including the PCA, between-class analysis, within-class analysis, HCA, ANOVA, and Tukey's test, were performed using the R software package (R Core Team, 2015).

3. A material flow analysis of livestock production

3.1. The nitrogen metabolism approach

The methodological approach was derived from the GRAFS approach (Generic Representation of Agro-Food Systems) as proposed by (Billen *et al.*, 2014). The GRAFS approach describes the agro-food system of a given area and considers flows of nutrients between four main compartments: cropland, grassland, livestock biomass, the local population. It also accounts for potential losses to the environment associated to flows exchanges among compartments (Le Noë *et al.*, 2017). We updated the original GRAFS calculations by attributing to livestock a more accountable position in the use of land-based resources. We thus considered livestock as a direct driver of flows, through feed sourcing from the crop and fodder compartments, rather than simply a compartment balancing out other flows as in the initial GRAFS approach (Billen et al., 2014).

Another important innovation consisted of characterising livestock heterogeneity at the finest level available. We compiled data on the diversity of current feeding systems; we distinguished 17 different types of feeding systems in dairy production, 9 types in beef production, 4 types in goat and sheep production, as well as to 5 types in poultry production and 2 types in pig production. Our method accounts for the local availability of feed resources, as all the diversity of feeding systems were calculated relative to a specific regional context. The system boundary was the department. A graphical representation is available in Figure **II-2** and compartments and flows calculation are described below.

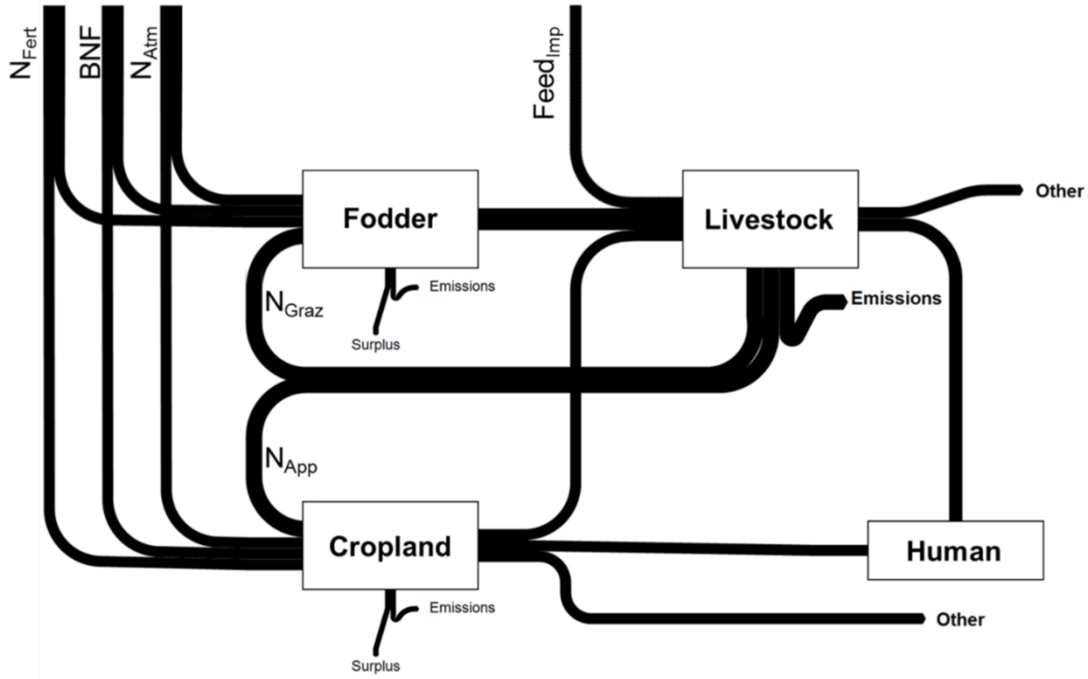


Figure II-2. Conceptualisation of the Nitrogen metabolism of livestock production, with four main compartments, and flows exchanges among them. N Fert: Nitrogen Fertilizer; BNF: Biological Nitrogen Fixation; N Atm: Nitrogem Atmospheric deposition; Feed Imp: Feed Imports; N Graz: N Excretion on Grazing; N App: N Excretion applied on cropland; Surplus: balance between inputs and outputs; Emissions: from manure and fertilizer application.

3.1.1. Livestock compartment and flows

Livestock production

Livestock numbers in both heads and livestock units were provided by the national agricultural statistics service (SSP, 2015). The livestock output was calculated taking in account productions of meat, milk and eggs from five group species (**Table II-3**) and their N content. Cattle, sheep, goat and pig production data was directly available in carcass-weight-equivalent (ton) or fresh milk production (hL) at the agricultural database (SSP, 2015). N content of diverse food and feed resources were informed in Lassaletta et al. (2014).

Table II-3. Livestock group species and class

Group species	Classes within group
Cattle	Beef and Dairy
Sheep	
Goat	
Pig	
Poultry	Chicken, laying hen, duck, turkey, guineafowl

Poultry production data was not directly available but could be determined according to equation X.

$$N_{Poultry\ Prod} = \sum_c Nb_c \times NbBatches_c \times LW_c \times D\%_c \times N_c \qquad (1)$$

where Nb_c was the number (heads) of poultry species of class c, $NbBatches$ the number of batches per year, LW_c the average live weight (kg), $D\%_c$ the dressing percentage (**Table II-4**) and N_c the related N content (% of carcass). Egg production ($kg.hen^{-1}.year^{-1}$) was estimated by multiplying the number of laying hens by 20.7 and the N content.

Table II-4. Poultry technical coefficients (ITAVI, 2012).

Poultry species	Number of batches	Live weight (kg)	Dressing %
Laying hens	1.00	1.86	60
Chicken	5.94	2.08	70
Turkey	2.56	9.92	75
Duck	3.48	3.96	65
Guineafowl	3.79	1.67	60

Livestock feed flows

An important aspect in the quantification of feed flows was to achieve a detailed characterization of the diversity of feeding systems existing across the departments studied. The high heterogeneity observed in ruminant production systems (cattle, sheep and goat) required an estimation of feed resource consumption that accounts for the diversity of their feed diets. This latter contrasts significantly across different farming systems with varied levels of specialization and availability of feed resources. We relied on Devun *et al.* (2012) reference tables of feed consumption, which quantified the existing diversity of feeding systems, summing up to 17 types in dairy production, 9 types in beef production, 4 types in goat and sheep production.

In qualitative terms livestock feed flows are made of two main flows, forage and concentrates. Forage flows were estimated with reference values of the tables of feed consumption (Devun *et al.*, 2012). The forage component of ruminants' diets provided estimates of the grass grazed and of the grass and maize for hay or silage making. The concentrate component for ruminants constitute the sum of cereals, protein-crops, soy-bean and other meals, co-products and amino acids and vitamins. Data was available at small agricultural region (SAR), situated between NUTS4 and NUTS5, with a total of 713 SARs, which was aggregated at NUTS3 level.

For monogastrics, the characterization of feed flows does not involve particularly a diversity of feeding systems, as the evolution of poultry and pig production was driven towards industrial production systems, with more strict formulation of diets. Our description of feed flows included however the detail of feed resources supply by the feeding industry for 5 poultry species and for growing pigs and breeding animals. Data was available at French supra-regional scale, situated between NUTS1 and NUTS2 level, with a total of 9 supra-regions. Feed flows were disaggregated to NUTS3 level, by distributing feed resources proportionally to livestock units. These feed flows represented the supply of compounded feed by the feed industry (FAB), that in 2010 accounted to roughly 79% of the total of monogastrics feed supply, the remaining part corresponding to on-farm produced feed. The on-farm produced feed (FAF) was estimated on the basis of similar composition of compounded feed, which both added up totalled 100%, then covering the feed consumption of monogastrics (Cereopa[1]).

$$FAF_{i,k} = FAB_{i,k} \times \frac{\beta_k}{(1-\beta_k)} \quad (2)$$

[1] Centre d'Etude et de Recherche sur l'Economie et l'Organisation des Productions Animales (http://www.cereopa.com/index.php)

where β_k was the share of FAF in the total feed resources consumption (e.g. sum of FAF and FAB) for feed resource *k*, and *i* each poultry species or growing pigs and breeding animals (**Table II-5** and **Table II-6**).

Table II-5. Values of β_k coefficient for pig production per French region (Source: Berthelot & Badouard, 2011).

Region	Coefficient β_k
Bretagne	0.29
Centre-Ouest	0.38
Centre-Est	0.62
Massif central	0.27
Nord	0.70
Nord-Est	0.83
Sud-Ouest	0.46
Normandie	0.32
National	0.34

Table II-6. Values of β_k coefficient for poultry production per poultry species in France (Source: Enquêtes SSP 1996, 2004, 2008)

Filière	Valeur coefficient β_k
Chicken	0.046
Turkey	0.005
Guinea fowl	0.096
Duck	0.105
Laying hens	0.175

Livestock excretion

Livestock nitrogen excretion was calculated following the tool *NOPOLU-Agri* of the National Service of Observation and Statistics (SOeS 2013). Details of calculations are explained in the following paragraphs. N excretion ($NExcr$) can take two paths, excretion during grazing through direct deposition of urine patches and dung on the field ($NGraz$) and excretion collected at livestock housing ($NHous$) (**Figure II-3**).

$$NExcr = \sum(NGraz + NHous) \quad (3)$$

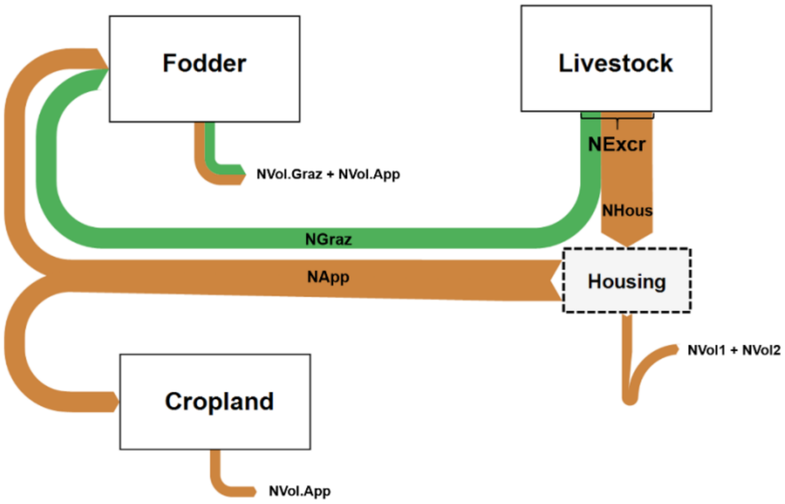


Figure II-3. Nitrogen excretion flows decomposition. NExcr: N excretion; NHous: N excretion on housing; NGraz: N excretion on grazing; NApp: N manure application; NVol: N volatilization on housing (NVol1), manure storage (NVol2), during grazing (NVol.Graz) and of application (NVol.App) (adapted from SOeS, 2013)

As cattle alone represents around 82% of total N excretion of all livestock species, a more detailed calculation process was undertaken to estimate the N excretion of dairy and beef herd (SOeS, 2013). To the other remaining species an excretion factor was applied per number of head (**Table II-7**).

Table II-7. Nitrogen excretion per livestock species and classes (Source: SOeS, 2013).

Livestock (species and classes)	N Excretion per head per year (kg)
Bovins mâles	12.000
Bovins femelles	20.000
Veaux de boucherie	6.300
Bovins mâles (1 an - 2 ans)	76.000
Bovins femelles (1 an - 2 ans)	53.000
Bovins mâles (>2 ans)	91.000
Génisses (> 2 ans)	61.000
Vaches laitières	118.000
Autres vaches	105.000
Brebis d'élevage	14.000
Autres moutons	7.000
Agnelles de souche	2.000
Chèvres d'élevage	14.000
Autres chèvres	7.000
Chevrettes pour la souche	14.000
Porcelets pesant moins de 20 kg	3.800
Truies d'élevage pesant 50 kg et plus	22.400
Autres porcs	12.400
Poulets / Standard	0.314
Poulets / Label AOC ou Bio	0.384
Poules pondeuses	0.713
Poulettes	0.313
Canards à rôtir / Standard	1.100
Canards à rôtir / Label AOC ou Bio	1.100
Canards gavage / Standard	2.200
Canards gavage / Label AOC ou Bio	2.200
Dindes et dindons / Standard	0.372
Dindes et dindons / Label AOC ou Bio	0.349
Oies / Standard	1.428
Pintades / Standard	0.316

For cattle, we estimate at first the total N excretion ($NExcr$), which is calculated as a function of the time cattle spend grazing:

$$NExcr = \sum_{c} (A_c \times TGraz + B_c) \times Nb_c \qquad (4)$$

where A_c and B_c were coefficients of a linear regression specific to the calculation of N excretion of cattle class c, under grazing duration $TGraz$ expressed as the share of time cattle spend grazing and Nb_c the number of heads of cattle (**Table II-8**).

Table II-8. Coefficients A and B of N excretion linear regression per cattle class. (Source: SOeS, 2013; adapted from CORPEN, 1999).

Cattle category	Coef. A	Coef. B	GrazCoef
Dairy cow	40	95	11.2
Suckler cow	67	60	10.6
Male < 1 year	0	12	2.8
Heifer < 1 year	4	18	3.3
Male between 1 and 2 years	12	68	6.6
Heifer between 1 and 2 years	19	42	5.1
Male >2 years	17	81	8.1
Heifer > 2 years	25	47	6.0

Next step consisted of estimating the share of N excretion that occurred during grazing (*NGraz*):

$$NGraz = \sum_{c} (12 \times GrazCoef_c \times TGraz) \times Nb_c \quad (5)$$

where $GrazCoef_c$ was the coefficient corresponding to the monthly N excretion (kg N.month^{-1}) of cattle class c during grazing. This calculation was applied to all cattle classes, except to calves, that were culled before they started grazing, so N excretion for this class was a fixed value.

Once total N excretion and N excretion during grazing were calculated, the difference between both variables enabled to estimate N excretion on livestock housing ($NHous$):

$$NHous = NExcr - NGraz \quad (6)$$

Volatilization of N at housing ($NVol1$) were calculated and determined the remaining amount of manure following to a storage unit. Volatilization also occurs during storage ($NVol2$) before treated manure can finally be applied as organic fertilizer. Manure management emission factors were specific to group species and classes, and depended on the type of manure produced, for instance liquid, slurry or solid. Emission factors were applied to each process and determined the available N to application as follows (**Table II-9**):

$$NApp = NHous - NVol1 - NVol2 \quad (7)$$

$$NVol1 = \sum_{c} NHous_c \times EF1_{c,m} \quad (8)$$

$$NVol2 = \sum_{c} (NHous_c - NVol1_c) \times EF2_{c,m} \quad (9)$$

where $NVol1$ and $NVol2$ are the N volatilization of manure on livestock housing and on manure storage facilities, respectively, and $EF1_{c,m}$ and $EF2_{c,m}$ are the related emission factors corresponding to livestock class *c* and manure management *m* and are reported as the percentage of N that is emitted.

Table II-9. Livestock excretion N-NH_3 emissions per type of species and place. (Source: SOeS, 2013).

	Dairy cow	Suckler cow	Sheep	Goat	Pig	Poultry
Grazing	10%	10%	10%	10%	10%	60%
Housing – slurry ($EF1$)	30%	30%	30%	30%	30%	50%
Storage slurry ($EF2$)	5%	5%	5%	5%	5%	20%
Application slurry	20%	20%	20%	20%	20%	20%
Housing solid manure ($EF1$)	25%	25%	25%	25%	24%	30%
Storage solid manure ($EF2$)	5%	5%	5%	5%	0%	15%
Application solid manure	10%	10%	10%	10%	10%	10%
Housing - laying hen manure ($EF1$)	-	-	-	-	-	30%
Storage laying hen manure ($EF2$)	-	-	-	-	-	30%
Application laying hen manure	-	-	-	-	-	10%

3.1.2. Land based compartments and flows, crop and fodder

Crop and fodder production

We characterized the land based compartments of crop and fodder production. We accounted for crop and fodder production that might have potential use as food for humans and as feed for livestock, with 10 types of fodder and 17 types of crops (**Table II-10**). Crop and fodder N harvest were calculated as follows:

$$NHarv = \sum_{i} (Y_i \times A_i \times N_i) \quad (10)$$

where Y_i was the yield (kg N.ha^{-1}.year^{-1}) of crop or fodder *i*, A_i was the area (ha) allocated and N_i was the N content (%) of the respective crop or fodder.

Table II-10. List of types of fodder and crops accounted for in this study.

Crop type	Fodder type
Soft wheat	Temporary grasslands
Triticale	Mix of grass and legumes
Durum wheat	Other annual forages
Rye	Artificial grasslands
Barley	Maize silage
Oat	Peas
Maize	Permanent grasslands
Rice	Low production grasslands
Other cereal crops	Faba bean and lupins
Sorghum	
Beans	
Potato	
Sugar beet	
Colza	
Sunflower	
Soybeans	
Linseed	

N inputs to land

The fodder compartment comprised the share of agricultural land occupied by permanent grasslands, annual and artificial grasslands, and cultivated forage (eg maize). The cropland compartment comprised the remaining share of the agricultural area cultivated mainly with cereals and oil-protein crops (see **Table II-10** for complete list of crops). The size of each compartment consisted in the sum of the total area allocated to each crop or fodder type. The livestock compartment its size corresponded to the sum in livestock units of the following species: cattle, sheep, goat, pig and poultry (add species names). The human compartment size was equal to the number of inhabitants. Inflows and outflows of each compartment were calculated in terms of N according to the equations provided below.

N inputs to land were synthetic fertilizers, biological nitrogen fixation, atmospheric deposition and organic fertilizer (animal excretion). N synthetic fertilizer use in crop and fodder production was calculated according to the following equation:

$$N_{Fert} = \sum_{i} IR_i \times A_i \quad (11)$$

where IR_i was the input rate (kg N.ha^{-1}.yer^{-1}) of N synthetic fertilizer for crop or fodder *i*, and $A_i$the area (ha) occupied/allocated by crop or fodder *i* under N synthetic fertilizer application.

N input resulting from legume crop and fodder biological nitrogen fixation (BNF) was calculated

$$BNF = \sum_i \left(\alpha_i \times \frac{Y_i}{NHI} + \beta_i\right) \times BGN \times A_i \times \%A_i \quad (12)$$

where α_i and β_i were the slope and intercept coefficients depending on crop species determined by regression analysis (**Table II-11**), Y_i was the harvested yield (kg N.ha^{-1}.year^{-1}), NHI was the N harvest index, defined as the ratio of the harvested material to the total aboveground production, and BGN was a multiplicative factor to take into account belowground contributions (comprising N associated with roots, nodules and rhizo deposition) that were set to 1.3 and 1.7 for grain and forage, respectively (Anglade et al., 2015). For cultivation of mix of grass and legumes a further factor $\%A_i$ was accounted as the share of the area of legume crops in the mixture.

Atmospheric deposition input to the agricultural area were available at the EMEP (European Monitoring and Evaluation Programme) at 50x50 km^2 grid resolution for dry and humid N deposition (mg/m^2.year^{-1}), which was further aggregated to the scale studied (NUTS3).

Table II-11. Coefficients for estimating fixation derived nitrogen in legume crops and fodder (Source: Anglade et al., 2015).

Crop - Fodder	α_i	β_i	NHI	BGN	$\%A_i$
Faba bean and lupin	0.78	3.06	0.90	1.7	1.00
Beans	0.70	1.01	0.75	1.3	1.00
Soybean	0.70	1.01	0.75	1.3	1.00
Mix of grass and legumes	0.78	3.06	0.90	1.7	0.30
Legume forages	0.81	-13.9	0.90	1.7	1.00
Peas	0.66	4.32	0.75	1.3	1.00
Natural grasslands	0.78	3.06	0.90	1.7	0.15
Low production grasslands	0.78	3.06	0.90	1.7	0.15

We calculated the total organic fertilizer application taking into account both the total available N ($NApp$), previously calculated in equation 6, and the crop and fodder areas under application of N organic fertilizer ($AOrg$), calculated as follows:

$$AOrg = \sum A_i \times \%Aorg_i \quad (13)$$

where $\%Aorg_i$ was the share of agricultural area allocated to crop and fodder *i* that was under application of N organic fertilizer (**Table II-12**).

Table II-12. Share of crop and fodder area under spread of organic fertilizer at country level (manure) (Source: SOeS 2013).

Crop/Fodder	Area
Wheat	12%
Triticale	32%
Durum wheat	4%
Rye	3%
Barley	13%
Oat	3%
Maize	40%
Maize irrigated	28%
Other cereals	3%
Sorghum	3%
Potato	35%
Sugar beet	56%
Rapeseed	33%
Sunflower	16%
Temporary grasslands	38%
Mixed legume grass	38%
Annual fodder	82%
Forage maize	82%
Peas	8%
Grasslands	25%

Next, we calculated the allocation of organic fertilizer:

$$N = \frac{NApp}{AOrg} \quad (14)$$

where $TotalNApp$ was uniformly distributed over the sum of crop and fodder areas receiving manure application $AOrg$.

N emissions to atmosphere

Emissions related to volatilization due to synthetic fertilizer application to land were accounted in terms of the proportional rate of the different types of fertilizers (e.g. Ammonium nitrate, Urea, NPK) used in each region (NUTS2). N-NH_3 emissions from synthetic fertilizer were calculated as follows:

$$Fert_{NH_3} = \sum NFert \times EF_{NH_3} \qquad (15)$$

where $\sum NFert$ was the total synthetic fertilizer application and $EF\ NH_3$ the N-NH_3 emission factor, reported as the percentage of N emitted (**Table II-13**).

Table II-13. Average coefficients of N-NH3 volatilization according to fertilizer type (share of synthetic fertilizer application) per region. (Source: SOeS 2013).

Region	Volatilization
Île-de-France	4,3%
Champagne-Ardenne	7,1%
Picardie	5,1%
Haute-Normandie	5,0%
Centre	5,5%
Basse-Normandie	3,9%
Bourgogne	3,9%
Nord-Pas-de-Calais	2,8%
Lorraine	6,0%
Alsace	5,7%
Franche-Comté	3,8%
Pays de la Loire	3,5%
Bretagne	3,1%
Poitou-Charentes	6,2%
Aquitaine	7,5%
Midi-Pyrénées	6,1%
Limousin	2,5%
Rhône-Alpes	3,9%
Auvergne	3,1%
Languedoc-Roussillon	4,3%
Provence-Alpes-Côte d'Azur	4,3%
France	**5,3%**

Emissions related to the N volatilization of NH_3 and of N_2O of livestock excreta occur during grazing, with urine and dung deposition on pastures and during application of N organic fertilizer on crops and fodder. Emissions were calculated as the product of $NGraz$ or $NApp$ by their respective emission factor, reported as the percentage of N emitted (**Table II-9**, **Table II-14** and **Table II-15**).

$$Graz_{NH_3} = NGraz \times EF_{NH_3} \qquad (16)$$

$$Graz_{N_2O} = NGraz \times EF_{N_2O} \quad (17)$$

$$NApp_{NH_3} = NApp \times EF_{NH_3} \quad (18)$$

$$NApp_{N_2O} = NApp \times EF_{N_2O} \quad (19)$$

Table II-14. Emission factors of N-N_2O and N_2 of different types of manure management and livestock species, as percentage of total N excretion. SOeS (2013).

Types of manure	N-N_2O	N_2
Slurry (all species except pig)	0,25 %	1,25 %
Solid (all species except pig and poultry)	0,50 %	2,50 %
Solid + straw (all species except poultry)	1,00 %	5,00 %
Slurry (pig)	0,20 %	1,00 %
Solid (pig)	4,00 %	29,00%
Laying hen manure	0,10%	0,50 %

Table II-15. Emission factors of N-N_2O from N excretion of livestock during grazing, as percentage of total N excretion. Source: SOeS (2013).

Livestock species	N-N_2O
Dairy cattle	2,0%
Beef cattle	2,0%
Goat	1,0%
Sheep	1,0%
Pig	2,0%
Poultry	2,0%

N surplus

The estimate of the potential N surplus in agro-ecosystems was calculated as the difference between N inputs and N outputs on the agricultural land compartments (fodder and cropland)(**Figure II-4**). Sum of N inputs was: synthetic fertilizer, organic fertilizer, biological nitrogen fixation and atmospheric deposition. Sum of N outputs was: crop and fodder products added to the N emissions to the atmosphere. No accounts on the dynamics of change in the soil organic N were considered. The surplus consisted therefore a measure of the potential N that could be lost to the environment and was calculated as follows:

$$NSurplus = \sum(NFert; BNF; NApp; NAtm) - \sum(Fert_{NH_3}; Graz_{NH_3}; App_{NH_3}; Graz_{N_2O}; App_{N_2O}) - \sum(NHarv.Crop; NHarv.Fodder) \quad (20)$$

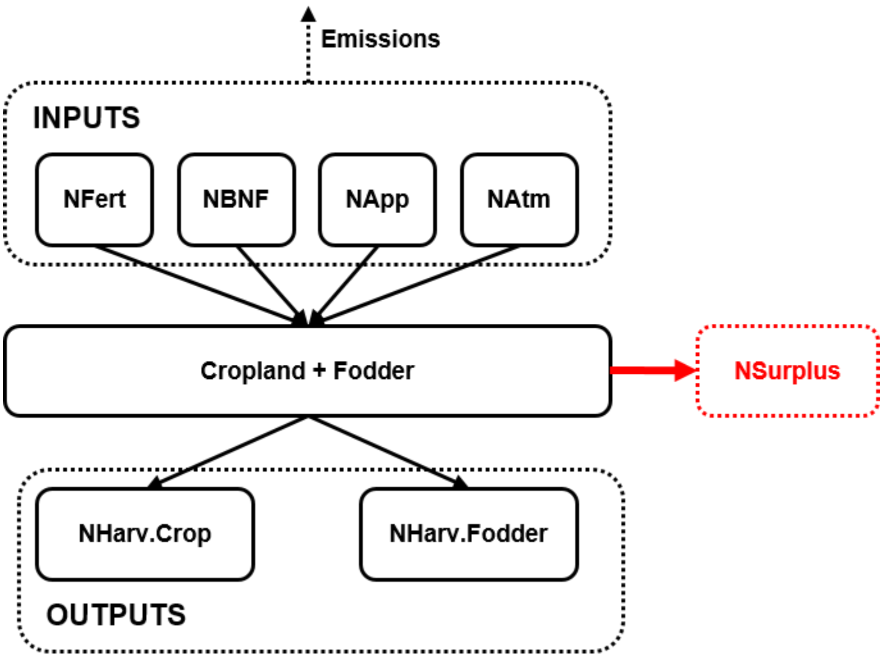


Figure II-4. The N surplus calculation.

Human consumption flows

The human food demand was estimated using the national average of food consumption per capita in 2010 (

Table II-16) and the size of the population of each department entity (NUTS3) obtained on INSEE[2] online databases.

Table II-16. National human food demand of crop and livestock products in France, 2010 (Agreste 2010).

		Consumption (kg/ per capita)	Nitrogen (%)
Crop products			
	Soft wheat	92.9	1.9
	Potatos	49.3	0.35
	Durum wheat	15.2	2.1
	Maize	4.4	1.4
	Barley	0.3	1.5
	Rye	0.3	1.4
	Peas	0.2	3.8
	Oat	0.2	1.9
	Faba beans	0.2	3.8
Livestock products			
	Dairies		
	- Fresh dairies	91.0	0.53
	- Yogurt	65.9	0.53
	- Cream	6.1	0.43
	- Condensed milk	0.8	1.26
	- Dried Milk	0.4	4.21
	- Dried Milk – skimmed	1.4	5.79
	- Butter	7.8	0.14
	- Cheese	23.9	4.00
	- Cheese fondue	1.5	4.00
	Pork	33.3	1.79
	Beef	25.8	2.64
	Chicken	16.0	3.47
	Eggs	13.9	1.71
	Turkey	5.0	3.65
	Goat	3.4	2.24
	Sheep	3.3	2.24
	Duck	3.1	3.65
	Guineafowl	0.5	3.65

[2] Institut national de la statistique et des études économiques (https://www.insee.fr/fr/statistiques)

3.1.3. Relationships between crop, livestock and human consumption

Once crop flows were estimated, we established a criteria for allocating flows between livestock (feed) and human (food). Crop flows first covered the human demand for food at NUTS3 level. Then, another part consisted on local feed resources available (NUTS3 level) to livestock nutrition (feed). The remaining part of crops flows was allocated to other uses (such as industrial and export (**Figure II-5**).

Estimates of local feed resources availability to livestock were calculated following a criterion of allocation based on the national use of crop resources (e.g. human consumption, industry, fuel, and livestock feed) (Agreste - Bilans d'approvisionnement agroalimentaires, 2015). The share (%) of each crop used as livestock feed (α_c) was calculated as follows:

$$\alpha_c = \frac{CropFeed_c}{Harv_c} \tag{21}$$

where $CropFeed_c$ was the quantity of crop feed *c* available to livestock, and $Harv_c$ was the total amount of crop harvested. Once α_c was calculated for all feed crops at national level, the total availability at department level (NUTS3) of feed resources to livestock (LAFCrop) was estimated as follows:

$$LAFCrop = \sum (LP_c \times \alpha_c) \tag{22}$$

where LP_c was the department (NUTS3) production of crop *c*, and α_c the share of crop *c* available as crop feed.

Another part of local available feed resources consisted of co-products derived from food processing industry, such as for wheat, sugar beet, maize and oil-crops. The determination of co-products resources available as livestock feed was calculated similarly to α_c , except for an intermediate step which accounts to the transformation of crops as raw products into processed end products as follows:

$$\beta_{cp} = \%Industry_c \times (1 - ExtRate_{cp}) \times \%Feed_{cp} \tag{23}$$

where β_{cp} was the share of co-product *cp* that was used as livestock feed, $\%Industry_c$ was the share of crop *c* that was processed in industry, $ExtRate_{cp}$ the extraction rate (or milling yield) from transformation of related crop *c* into a given end product, and $\%Feed_{cp}$ the share of co-product *cp* used as livestock feed. Once β_{cp} was calculated for all co-products, the available co-products at local level (NUTS3) was estimated:

$$LAFCoproduct = \sum (LP_c \times \beta_{cp}) \tag{24}$$

where LP_c was the local production (NUTS3) of crop *c*, and β_{cp} the share of the co-product *cp* related to crop *c* that was used as livestock feed. α_c and β_{cp} coefficients of feed resources are available at **Table II-17** and **Table II-18**. The sum of LAF_{crop} and $LAFCoproduct$ determined the total feed resources available to livestock. (adapted from EFESE[3]).

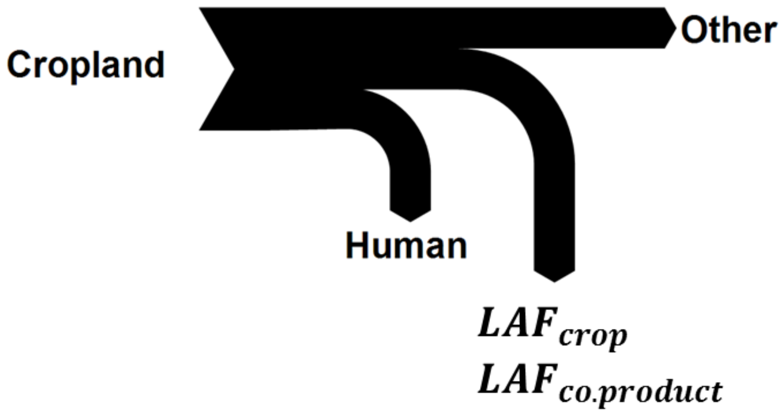


Figure II-5. Schematic representation of crop nitrogen flows allocation as food for humans, and as feed for livestock (LAF_{Crop} and $LAF_{Coproduct}$) and other uses.

Lastly, livestock import flows are calculated as the difference between the total feed consumption minus the local available feed resources (**Figure II-6**).

[3] L'évaluation française des écosystèmes et des services écosystémiques (EFESE, 2017)

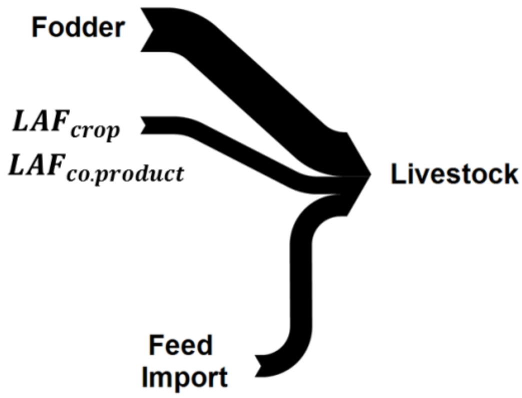


Figure II-6. Decomposition of livestock feed consumption flows : fodder, local available feed resources (LAFCrop and LAFCoproduct) and feed import.

Table II-17. Coefficient *αc* for estimates of local availability of feed crop resources used as livestock feed (adapted from EFESE)

Feed crop resources	α_c
Soft wheat	0.023
Durum wheat	0.005
Barley	0.035
Oat	0.088
Rye	0.055
Triticale	0.090
Maize	0.032
Sorghum	0.068
Rapeseed	0.004
Sunflower	0.013
Soya beans	0.063
Linseed	0.148
Peas	0.109
Faba beans	0.064
Lupin	0.282

Table II-18. Coefficient β_{cp} for estimates of local availability of co-products resources used as livestock feed (adapted from EFESE[4])

Crop	Co-product	β_{cp}
Sugar beet	Beet pulp (dehydrated)	0.0031
	Molasses	0.00019
Soft wheat	Mill co-products	0.00500
Maize	Corn gluten feed	0.00800
	Gluten 60	0.00390
Soybean	Soybean meal	0.15170
Rapeseed	Rapeseed meal	0.10170
Sunflower	Sunflower meal	0.08870

3.2. Indicators derived from the inventory of N flows

From the inventory of N flows we derived metrics to describe livestock systems at department level in terms of their performance and impacts. We built a multi-criteria set of indicators that cover different dimensions of livestock system sustainability. Six indicators measured efficiency of fodder and livestock production, department feed self-sufficiency and animal source food supply, as well as impact measures from local and global perspectives. Indicators related to environmental objectives with a regional target were area-based; whereas indicators with a global focus, such as nitrogen emissions were product-based (Halberg et al., 2005). A description of each indicator is provided below.

- *Fodder Nitrogen Use Efficiency (NUE)*

The NUE indicator reports the efficiency of fodder to transform N inputs to the soil into N harvested end products to livestock (Connant et al. 2013). It constitutes an important account of resources use efficiency as livestock overall sustainability largely depends on the efficiency of which feed is produced.

$$Fodder\ NUE = \frac{NHarv}{\sum Inputs} \quad (24)$$

where $NHarv$ was the N harvested of fodder production, and $\sum Inputs$ was the sum of all N inputs (fertilizers, fixation, organic application, deposition) used in the fodder cultivation.

- *Livestock Nitrogen Feed Conversion Ratio (FCR)*

The N FCR is a measure of the plant to animal protein conversion efficiency, which indirectly determines the remaining amount of excreted N that can be recycled back to agricultural land in the form of organic fertilizer or end up in water streams and cause environmental pollution (Billen et al. 2014).

$$N\ FCR = \frac{\sum ASF}{\sum FeedCons} \quad (25)$$

where $\sum ASF$ is the total N recovered in livestock products of all species, and $\sum FeedCons$ the sum of N in feed resources consumed.

- *Nitrogen Self-Sufficiency (NSS)*

The NSS is an indicator that measures the capacity of regions to provide local feed resources in order to meet local livestock feed demand (EFESE[4]).It was calculated as follows:

$$NSS = \frac{\sum LocalFeed}{\sum FeedCons} \tag{26}$$

where $\sum LocalFeed$ was the sum of N in local supply of livestock feed resources, and $\sum FeedCons$ the sum of total N in feed resources consumed by all livestock species.

- *Animal Source Food (ASF)*

The ASF indicator comprises the sum of N in livestock production (ton) including: beef and dairy, sheep and goat meat and milk, pork, poultry meat and eggs. It was computed in terms of nitrogen and represents the local ability a region has to provide human-edible animal protein (Speedy, 2003).

- *N surplus (NSU)*

The estimate of the potential N surplus was calculated as the difference between N inputs and N outputs on fodder and cropland. We calculated the N surplus (kg) reported per hectare of crop area as a measure of N pressure, thus representing the potential local impact caused by livestock (Poisvert et al., 2017). The details of N surplus calculation is available in equation 20.

- *N Excretion Emissions (NEE)*

N Excretion Emission included emissions related to the N volatilization of NH_3 and the emission of N_2O derived from livestock excreta during grazing (with urine and dung deposition on pastures). Emissions also included volatilization during housing and in manure storage facilities, and application of N organic fertilizer on crops and fodder (Webb et al., 2005; Lesschen et al., 2011). We calculated the N Excretion Emissions (kg) reported per kg of ASF as a measure of potential global impact caused by livestock.

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[4] L'évaluation française des écosystèmes et des services écosystémiques (EFESE, 2017)

3.3. Analysis of synergies and trade-offs

Six indicators were computed (**Table II-19**) for a set of 48 which gathered the main livestock areas and both extremes of intensification trajectories (Domingues et al. 2017). The six indicators were combined two at a time, which resulted in 15 interactions.

$$C_{n,p} = \frac{n!}{p!\,(n-p)!}$$

$$C_{6,2} = \frac{6!}{2!\,(6-2)!} = \frac{6 \times 5 \times 4 \times 3 \times 2 \times 1}{2 \times 1 \times (4 \times 3 \times 2 \times 1)} = \frac{6 \times 5}{2} = 15 \text{ interactions}$$

The Pearson correlation coefficients were calculated for all interactions (using package “Hmisc” version 3.4.1 for R - R Core Team, 2015). Eleven presented moderate or strong correlations, and four showed weak correlations (**Table II-19**). The eleven interactions were classified according to their nature, as a synergy or a trade-off. We considered a synergistic interaction when two desirable results can be jointly increased. A desirable result can mean two things: i) improvement, if it was a performance indicator; or (ii) reduction, if it was an environmental impact indicator. Similarly, we consider a trade-off interaction when a desirable result of one indicator was increased at the cost of an undesirable result of another indicator. An undesirable result can mean two things: i) reduction, if it was a performance indicator; or ii) increase, if it was an indicator of environmental impact.

Table II-19. Indicators classified by performance or environmental impact , and Pearson correlation coefficients, and the nature of the interactions (synergy or trade-off).

		NUE	FCR	NSS	ASF	NSU	NEE
Performance	NUE	1.00					
	FCR	-0.41	1.00				
	NSS	0.68	-0.52	1.00			
	ASF	-0.61	0.71	-0.69	1.00		
Environmental Impact	NSU	-0.89	0.65	-0.61	0.66	1.00	
	NEE	0.19	-0.93	0.38	-0.58	-0.44	1.00

NUE: Fodder Nitrogen Use Efficiency; FCR: Nitrogen Feed Conversion Ratio; NSS: Nitrogen Self-Sufficiency; ASF: Animal Source Food; NSU: Nitrogen Surplus; NEE: Nitrogen Excretion Emissions. Only interactions having moderate to high correlation coefficient are classed as synergy (green) or trade-off (orange). Weak correlation interactions are coloured in grey.

3.4. Decomposition and mapping of synergies and trade-offs

Bag plots were used to decompose trade-offs and synergies and map their spatial variation across 48 departments. The Bagplot, is a bivariate boxplot; it was proposed by Rousseeuw et al. (1999) as tool for visualising the location, spread, correlation, skewness, and tail of data sets. It complement correlation coefficients and is a useful tool for mapping the spatial variation of trade-offs and synergies (Jolke et al, 2015).

Five steps were implemented for mapping the existing geographical patterns of performance and impact of livestock across departments. In the first step, we considered the different distribution of each indicator and transformed them for reducing skewness and data spread. The last column of **Table II-20** contains the factors we used to transform the indicators. In the second step we z-standardized the transformed data to a mean of zero and standard deviation of one, allowing meaningful comparisons among indicators. Third step consisted of making the bagplots with the use of package "aplpack" version 1.3.0. In the fourth step we selected interactions that had moderate or strong correlations ($r > 0.5$; $r < -0.5$) and used the bagplot's depth median as a reference point to separate each interaction into four quadrants (**Figure II-7a**). The first quadrant (positive/positive space), contains departments that perform well relative to the depth median, thus labelled superior positioning. The third quadrant (negative/negative space), contains departments that had weak performance relative to the depth median, thus labelled inferior positioning. The second and fourth quadrant, positive/negative and negative/positive spaces, respectively, contain departments that perform well for one indicator and weak for the other, thus labelled intermediate positioning.

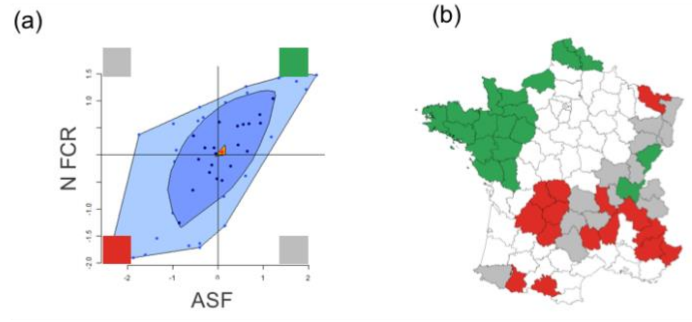

Figure II-7. Spatial decomposition of interactions among performance and impact indicators of livestock production, applied with the use of bagplots (a) to 48 NUTS3 units in the map of France (b). Green: Superior; Red: Inferior; Grey: Intermediate ASF: Animal Source Food; FCR: Nitrogen Feed Conversion Ratio.

In the fifth step, we used the ‘ggplot2’ package version 1.2.3 to map each interaction, and distinguish departments according to their performance or impact (superior, inferior, etc). **Figure II-7a-b** presents the spatial decomposition from bagplots graphs to maps of France’s departments. Another two figures are presented in the Supplementary Material S2 of paper 2, with bagplots for all interactions analysed.

Table II-20. List of indicators used in bagplots with respective units and transformation factors.

Type	Indicator	Unit	Transformation
Performance	Fodder Nitrogen Use Efficiency	%	$x^{0.9}$
	N Feed Conversion Ratio	%	$x^{0.9}$
	Animal Source Food	t of N	$x^{0.2}$
	N Self-sufficiency	%	$x^{0.9}$
Environmental	N Surplus	kg N ha^{-1}	(-1) . log(1+x)
Impact	N Excretion Emissions	kg N kg ASF^{-1}	(-1) . $x^{0.2}$

3.5. Classification of spatial patterns of synergies and trade-offs

After mapping the decomposition of 11 interactions we counted the frequency of events of each category (superior, inferior and intermediate) per department (**Table II-21**). Upon the table of counts we did a principal component analysis (PCA) to identify spatial patterns associated with departments’ performance and impacts. A post-hoc hierarchical cluster analysis (HCA) was done on the two components with eigenvalue > 1 of the PCA to identify groups of departments with homogenous characteristics for the indicators studied.

Table II-21. Number of counts of positioning of synergies and trade-offs among performance and impact indicators at the department level: ‘Superior’, ‘Inferior’ and ‘Intermediate’ (NUTS3).

	Synergy			Trade-off		
NUTS3	Superior	Inferior	Intermediate	Superior	Inferior	Intermediate
1	4	0	2	3	0	2
4	3	3	0	0	0	5
5	1	3	2	0	1	4
6	1	3	2	0	1	4
7	0	4	2	0	5	0
9	3	3	0	0	0	5
12	3	1	2	3	0	2
14	3	1	2	2	0	3
15	3	1	2	3	0	2
19	3	3	0	0	0	5
22	3	3	0	0	0	5
23	3	3	0	0	0	5
24	0	4	2	0	3	2
25	6	0	0	5	0	0
29	3	3	0	0	0	5
35	3	3	0	0	0	5
38	3	1	2	0	0	5
39	2	0	4	1	1	3
42	1	1	4	0	2	3
43	4	0	2	2	0	3
44	3	3	0	0	0	5
46	1	3	2	0	2	3
48	0	4	2	0	3	2
49	3	3	0	0	0	5
50	3	3	0	0	0	5
53	3	3	0	0	0	5
56	3	3	0	0	0	5
57	3	1	2	0	0	5
59	3	1	2	2	0	3
61	3	1	2	2	0	3
62	3	1	2	2	0	3
63	3	1	2	3	0	2
64	1	1	4	2	1	2
65	3	3	0	0	0	5
67	4	0	2	2	0	3
68	4	0	2	2	0	3
69	2	0	4	1	1	3
70	4	0	2	2	0	3
71	3	1	2	3	0	2
72	3	3	0	0	0	5
73	2	0	4	1	1	3
74	2	0	4	1	1	3
76	3	1	2	2	0	3
79	1	3	2	0	0	5
85	1	3	2	0	0	5
87	3	3	0	0	0	5
88	4	0	2	2	0	3
90	4	0	2	2	0	3

4. Linking intensification trajectories to the provision of social, environmental and cultural services

The influence of intensification trajectories on the current provisioning of environmental, cultural and rural vitality services by the livestock sector was assessed at department level. From a total of 95 French metropolitan departments, a subset of 60 was selected according to the livestock specialization coefficient of each department. Livestock specialization coefficient was calculated as the proportion of total NUTS 3 farms that were livestock farms. Departments with a coefficient of livestock specialization above 0.5 were selected; above this threshold we considered that livestock plays a role on services provision through its link to land and resources use.

Two data sets were used to describe intensification trajectories and service provision. The first data set characterized changes in the process of intensification between 1938 and 2010. It included three categories of variables describing: livestock, land use and socioeconomic dimensions (**Table II-22**) and already used for our first analysis (see ref to the section where the data set is described).

Table II-22. Variables considered in the analysis of change in the intensification process of the livestock sector.

Variables	Units
<u>Livestock variables</u>	
Herbivore stocking rate	$LU.ha^{-1}$
Monogastric stocking rate	$LU.ha^{-1}$
Herbivore meat production per main fodder area (cattle, sheep, and goat meat)	$kg.ha^{-1}$
Milk production per main fodder area (cow, sheep, and goat milk)	$kg.ha^{-1}$
<u>Land-use variables</u>	
Share of utilised agricultural area in the department	-
Share of main fodder area in utilised agricultural area	-
<u>Socioeconomic variables</u>	
Average farm size	ha
Labour productivity	$ha.AWU^{-1}$
Dependence ratio (purchased feed/ final livestock output)	-
Tractor density	$tractors.ha^{-1}$

To make meaningful comparisons among intensification variables and detect the direction and rate of change in the intensification process between 1938 and 2010, each numeric variable was divided by its average department value. The rate of change was calculated subtracting 1938 from 2010 observations. Variable values equal or close to zero meant the rate of change was similar to the average department. Negative variable values meant the rate of change was lower than observed in the average department. Positive variable values meant the rate of change was higher than observed in the average department.

The second data set characterized the provision of services by the livestock sector and was organized in three categories of variables: rural vitality, environmental and cultural (**Table II-23**). The rural vitality category included variables related to employment in livestock farms, in the agro-food industry and the contribution of the sector to overall employment. This category provides an account of the economic relevance of the livestock sector, which in Europe represents 42% of the total agricultural activity and provides employment to nearly 30 million people (Livestock, 2017). The environmental category included variables related to high nature value areas i.e. areas sustaining high levels of biodiversity (add ref to HNV), grasslands bird biodiversity (Teillard et al., 2015) and water quality. This category includes variables that account for aspects about the multifunctionality of farming systems, associated to the maintenance of habitat diversity and wildlife, and supporting services like nutrient cycling and water purification (Andersen et al., 2003; Power, 2010). The cultural category included variables related to heritage landscapes, agrotourism and heritage animal products. Although cultural services consists on immaterial benefits provided , they can be directly experienced and intuitively appreciated by people, such as aesthetic, social relations, recreational and heritage aspects (Plieninger et al., 2013). Data for service provisioning variables were developed by Ryschawy et al. (2017). The reference year was 2010.

Table II-23. Indicators selected to characterize services provided by the livestock sector. Adapted from Ryschawy et al. (2017).

Services	Indicator	Code	Unit
Rural vitality			
Employment in livestock farms	Workforce on livestock farms	EmpFarm	AWU
Employment in livestock agrofood industry	Employees in livestock agrofood industry	EmpInd	Number
Contribution of livestock to employment	Contribution of livestock sector to overall employment	Employ	%
Environmental			
High Nature Value of landscape	Area classified as High Nature Value	HNV	% UAA
Conservation of biodiversity	Proportion of grassland birds in bird community	Biodiv	%
Water quality	Proportion of municipalities outside nitrate vulnerable zones	Water	%
Cultural			
Heritage landscapes	Areas in heritage landscapes (grassland, specific areas, and trees)	Landscape	%
Agrotourism	Proportion of farms practicing agrotourism	Agrotourism	%
Heritage animal products	Number of quality-labelled animal products (SIQO)	Product	%

* AWU: Annual work unit; UAA: Utilized agricultural area

Statistical analysis

The analysis of the relationship between the intensification process and the provision of services by the livestock sector included three major steps: principal component analysis (PCA), co-inertia analysis, and a hierarchical cluster analysis (HCA). These three major steps are preceded by study of the correlation coefficients between variables of first and second data sets, for identification of interactions between the two data sets. The three major steps are explained, as follows:

First, a PCA was performed on the first and second data sets, to reduce the number of variables while keeping the largest possible variance. In the first data set four components were retained, explaining 72% of the total variance (eigenvalue >1). On the second data set three components were retained and explained 80% of the total variance (eigenvalue >1). The two PCA generated two tables that were used as inputs to the second step of the statistical analysis.

Second, a co-inertia analysis was performed on the two tables. The co-inertia analysis enable simultaneous analysis of two tables, and identifies the underlying data structure, and relationships between them (Dolédec and Chessel, 1994; Dray et al., 2003). It finds ordinations from the two data sets by similarity, by searching successive orthogonal axes from the two data sets with maximum squared co-variance. A complementary Monte Carlo permutation test follows the co-inertia analysis, to verify the significance of co-structure between tables. It was carried out on the two tables for 1000 permutations.

Third, a HCA was performed on the normed row scores, which is an output of co-inertia analyses. Complying with the Euclidean distance and Ward's aggregation method the HCA generated three groups of departments. Results presented in the form of tables, graphs and maps, were computed using the R software package (R Core Team, 2015). An analysis of variance (ANOVA) followed by the Tukey's test was performed on results related to changes in the intensification process and provision of services.

III.RESULTS

1. Driving factors of intensification process of livestock sector

1.1. National changes in livestock production

At the national level, the most important changes in the livestock intensification process were observed in the socioeconomic variables, with a 4-fold increase in the indicators of mechanisation and labour productivity between 1938 and 2010 (**Table III-1**). Further, tractor density rose from 0.0012 tractors per ha in 1938 to 0.0053 in 2010, and labour productivity increased from 8.6 ha per annual work unit (AWU) in 1938 to 35.9 ha in 2010. **Table III-1** also indicates a significant reduction in the number of farms, from 2 million in 1938 to 0.5 million in 2010, which contributed to farm enlargement.

Table III-1. National changes in livestock production, land use, and socioeconomic variables in France

	1938	1955	1970	1980	1988	2000	2010	1938-2010
Livestock Units (LU)	17 916	18 636	22 031	24 210	28 951	28 112	26 368	47%
Herbivore LU	14 624	15 211	17 381	18 917	22 503	20 090	18 787	28%
Herbivore Stocking Rate	0.47	0.51	0.54	0.61	0.79	0.73	0.70	50%
Monogastric LU	3 292	3 426	4 650	5 293	6 448	8 022	7 582	130%
Monogastric Stocking Rate	0.10	0.11	0.14	0.17	0.23	0.29	0.28	170%
Herb meat product: MFA	60	75	93	118	99	124	118	95%
Milk production: MFA	758	933	1127	1473	1576	1807	1856	145%
Utilised Agric. Area (UAA)	31 359	29 978	32 114	30 995	28 471	27 700	26 795	-15%
Main Fodder Area (MFA)	18 806	19 102	17 703	16 433	14 503	12 778	12 380	-34%
UAA: Department Area	0.58	0.55	0.59	0.57	0.52	0.51	0.49	-15%
MFA:UAA	0.60	0.64	0.55	0.53	0.51	0.46	0.46	-23%
Number of farms	2 067	2 246	1 578	1 255	1 012	660	487	-76%
Annual Work Unit (AWU)	3 637	3 381	2 290	1 863	1 439	953	747	-79%
Average farm size	15.2	13.3	20.4	24.7	28.1	42.0	55.0	263%
Labour productivity	8.6	8.9	14.0	16.6	19.8	29.1	35.9	316%
Dependence ratio	0.15	0.18	0.21	0.28	0.25	0.26	0.28	78%
Tractor density	0.0012	0.0020	0.0052	0.0059	0.0053	0.0052	0.0053	337%

See Table **II-2** for variable units.

Important gains were also detected in the livestock variables. The stocking rate of monogastrics increased approximately 170%, due to the rising population of monogastrics (+130%), which was concurrent with a slight reduction in the utilised agricultural area (-15%). Conversely, the apparent increase in the herbivore stocking rate was much smaller (+50%). Milk production per unit of main fodder area (MFA) increased by a factor of 2.4, from 758 kg per ha to 1,856 kg per ha over the period studied. Herbivore meat production per MFA roughly doubled, from 60 kg.ha-1 in 1938 to 118 kg.ha-1 in 2010, reaching peak production in 2000 (124 kg.ha-1) and returning to the 1980 level (118 kg.ha-1) by 2010. Increases in milk and meat production were mainly due to improved livestock performance in terms of meat and milk yield per animal, which was aided by a smaller but intensified MFA. The livestock sector relied more on external inputs in 2010 than in 1938, with the dependence ratio increasing by 78% over the period. This was partly due to a higher share of monogastrics in the total livestock population, rising from 18% to 28%, as monogastrics relied more on purchased feed concentrate than herbivores.

The results at the department level differed. In 1938, there was a close and local linkage between livestock and land use across the country, as 80% of the departments had allocated at least 50% of the UAA to fodder production (**Figure III-1**), and livestock were present in all departments (**Figure III-2**). In 2010, a more specialised pattern of land use was observed, with formerly dominant fodder land being cleared for cropland. Only 50% of the departments had allocated at least 50% of the UAA to fodder production (**Figure III-1**), and the livestock population was concentrated in a limited number of departments located in the Western and Central areas of France (**Figure III-2**). Combined, the two areas hosted approximately 80% of the national livestock population in 2010.

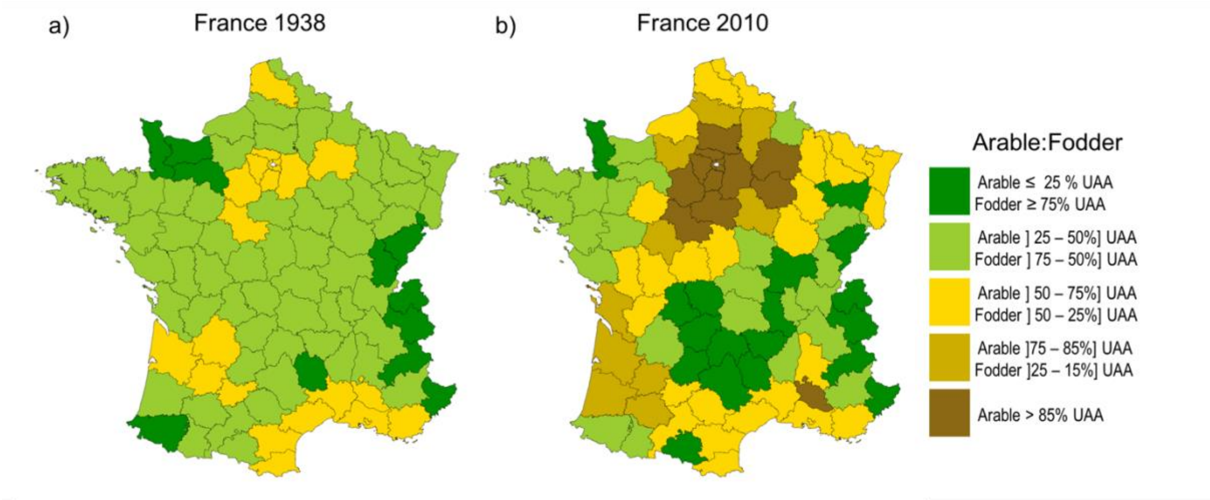

Figure III-1. The evolution of land use in France at the department level from 1938 (a) to 2010 (b) in terms of arable crop and main fodder area in utilised agricultural area.

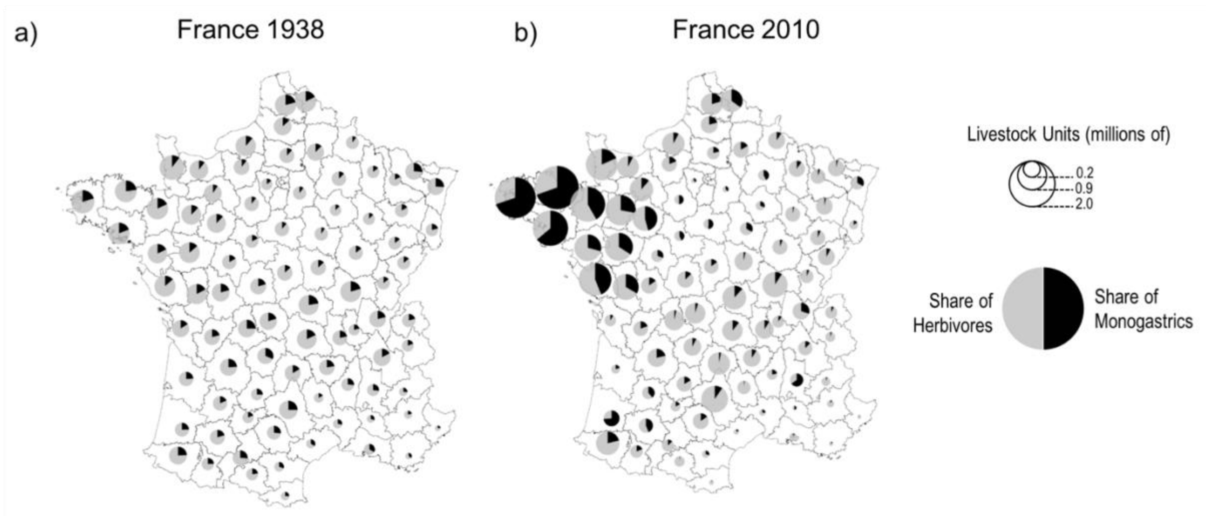

Figure III-2. The changes in the livestock population of herbivores (cattle, sheep, goat, horse) and monogastrics (pig, poultry) and in the species composition over time in France at the department level from 1938 (a) to 2010 (b).

1.2. The spatial differentiation of the intensification process in France

The within-class analysis conducted on data from the entire set of departments resulted in the identification of three factors with an eigenvalue >1. These factors explained 30.6%, 22.1% and 20.1% of the total variance, respectively. Factor 1 was primarily related to the combination of herbivore milk and meat production and the stocking rates of herbivores and monogastrics, and corresponded to a gradient in livestock production intensification, ranging from departments with high productivity and stocking rates to departments with a limited number of livestock. Factor 2 was generally positively related to the share of MFA and herbivore stocking rate, and negatively related to the average farm size and labour productivity, ranging from departments that emphasised grazing to departments that specialised in cropland. Factor 3 was mainly positively related to the dependence ratio and the monogastric stocking rate and negatively related to the share of MFA and herbivore stocking rate, ranging from a greater dependence on purchased feed and an increased monogastric population to a reduced dependence on purchased feed and a larger number of herbivores. The HCA identified four groups of trajectories within the departments. **Figure III-3** shows the projection of these four groups on the first and second components of the within-class analysis. **Figure III-4** shows the projection of the trajectories on a NUTS3 level map of France. **Figure III-5** shows the quantitative changes in the selected variables for each trajectory. A table listing the quantitative changes in all variables is available in the Supplementary Table S1.

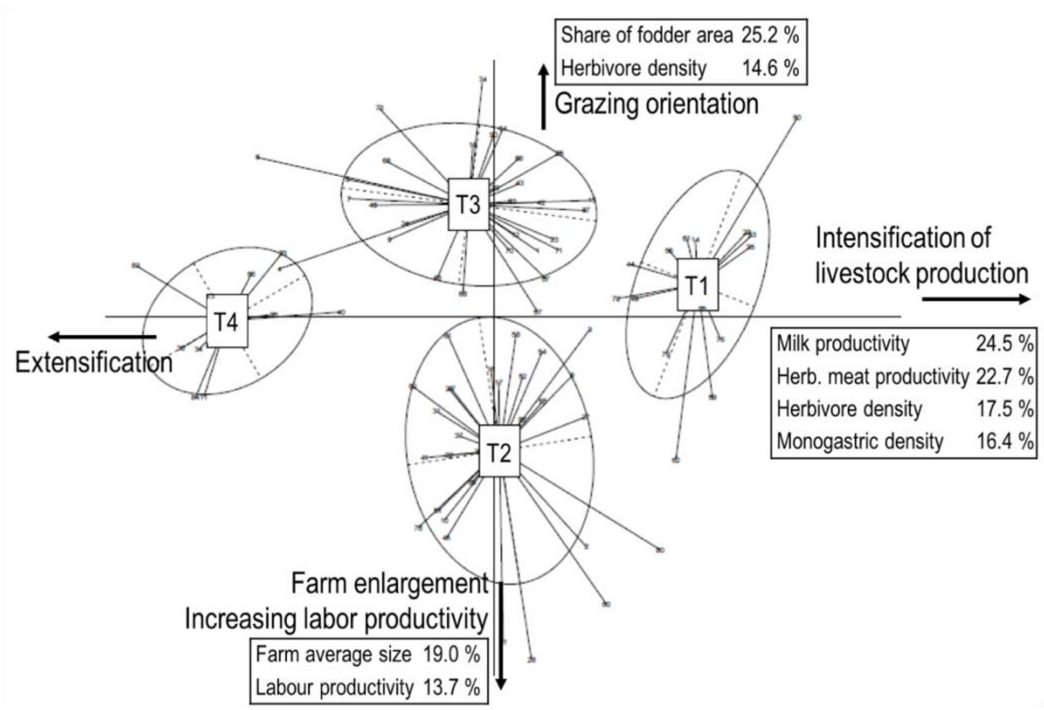

Figure III-3. Projection of the four types of trajectories on the first and second components of the within-analysis after the hierarchical cluster analysis. Each trajectory is formed by individual departments with similar intensification trends. The main variables and their contribution to the variance of components 1 and 2. Component 1 explained 30.6% of the variance between the departments. Component 2 explained 22.1% of the variance.

The type 1 trajectory (T1; n = 16) included the departments located in Western France that were characterised by the most intensive livestock production systems. The type 1 trajectory also exhibited the most significant increases in livestock numbers and productivity indicators, with the inherent animal populations and productivity more than doubling. Further, the most marked characteristic of this cluster was the size of its population of monogastrics, which increased 6-fold from an average of 59,000 livestock units (LU) in 1938 to 344,000 LU in 2010. In 2010, T1 hosted 72% of the monogastric population in the country. The 7-fold increase in the monogastric stocking rate, from 0.12 LU.ha-1 in 1938 to 0.84 LU.ha-1 in 2010, was higher than the population growth due to the concurrent 15% decrease in the UAA. Important gains in productivity were achieved, with milk production per ha of MFA rising from 990 litres in 1939 to 3,773 litres in 2010. This productivity gain was nevertheless realised at the expense of the dependence ratio, which almost tripled and was the highest among all trajectories in 2010. The higher dependence ratio reflected a characteristic of very intensive systems such as in landless monogastric or dairy production that relied heavily on purchased feed. As well, a 9-fold increase in mechanisation was necessary to sustain the livestock demand for feed (maize cropping and haymaking). Such gains in mechanisation contributed to the 4-fold gain in labour productivity, which increased from 8.8 ha per AWU in 1938 to 35.6 ha.AWU-1 in 2010.

The type 2 trajectory (T2; n = 30) included departments located in the core and surrounding Parisian Basin that were characterised by crop or mixed crop-livestock systems. The T2 departments were primarily distinguished by the highest total increase in the average farm size and in labour productivity. Farm enlargement was followed by arable crop expansion over the MFA. There was a small decline in livestock units (-4%) over the period between 1938 and 2010, with a slight decrease in herbivores (-6%) and a concurrent small increase in monogastrics (+8%). In 2010, herbivore meat and milk production equalled 126 kg and 1,736 kg per ha of fodder area, respectively, which corresponded to increases of 117% and 138% over the period, respectively.

The type 3 trajectory (T3; n = 32) included departments located in the East and central mountainous areas with an emphasis on grazing systems. Although trajectories T1, T2, and T4 lost MFA to crop land, T3 was the only trajectory that displayed a slight increase in MFA in the UAA (+5%). On average, MFA accounted for 73% of the UAA in 2010. The herbivore population underwent a 50% increase between 1938 and 2010, whereas the population of monogastrics declined by 35%. The emphasis on grazing relied predominantly on local fodder resources and was associated with a moderate increase in the 'dependence ratio' of 64% during the period compared to its 300% increase in T1.

The type 4 trajectory (T4; n = 10) included departments located in the Mediterranean and South-West regions, which experienced the highest UAA (-28%) loss rate, dropping from 226,000 ha in 1938 to 162,000 ha in 2010. In 2010, UAA accounted for 26% of the department areas, which was far below the country average of 49%, indicating the minor importance of agriculture in this cluster. A 48% reduction in MFA, from 91,800 to 47,600 ha, was observed along with a halving of the herbivore population from 67,000 in 1938 to 34,100 LU in 2010. As well, the T4 cluster had no significant emphasis on livestock production compared to the other clusters. Livestock productivity was low and tended to decline between 1938 and 2010 with meat and milk production per ha of MFA falling from 39 kg to 32 kg and from 616 litres to 444 litres, respectively.

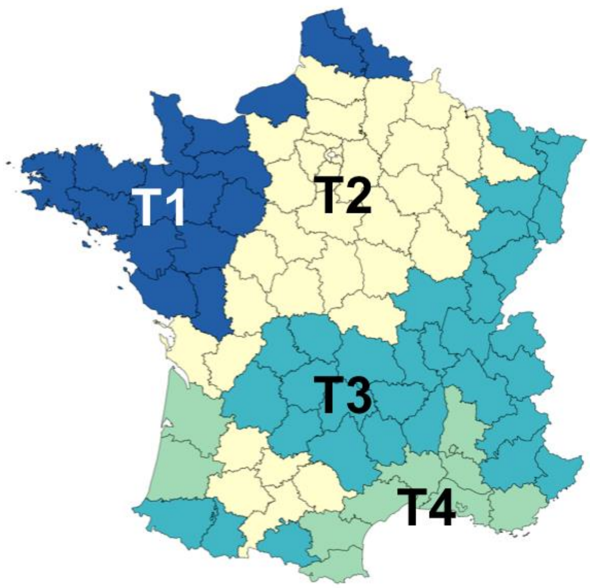

Figure III-4. Location of the four intensification trajectories in France at the department level. T1, 2, 3, and 4 correspond to 'High intensification of livestock production', 'Crop orientation and intermediate intensification of livestock', 'Grazing orientation of livestock production', and 'Non-livestock dominated' departments, respectively.

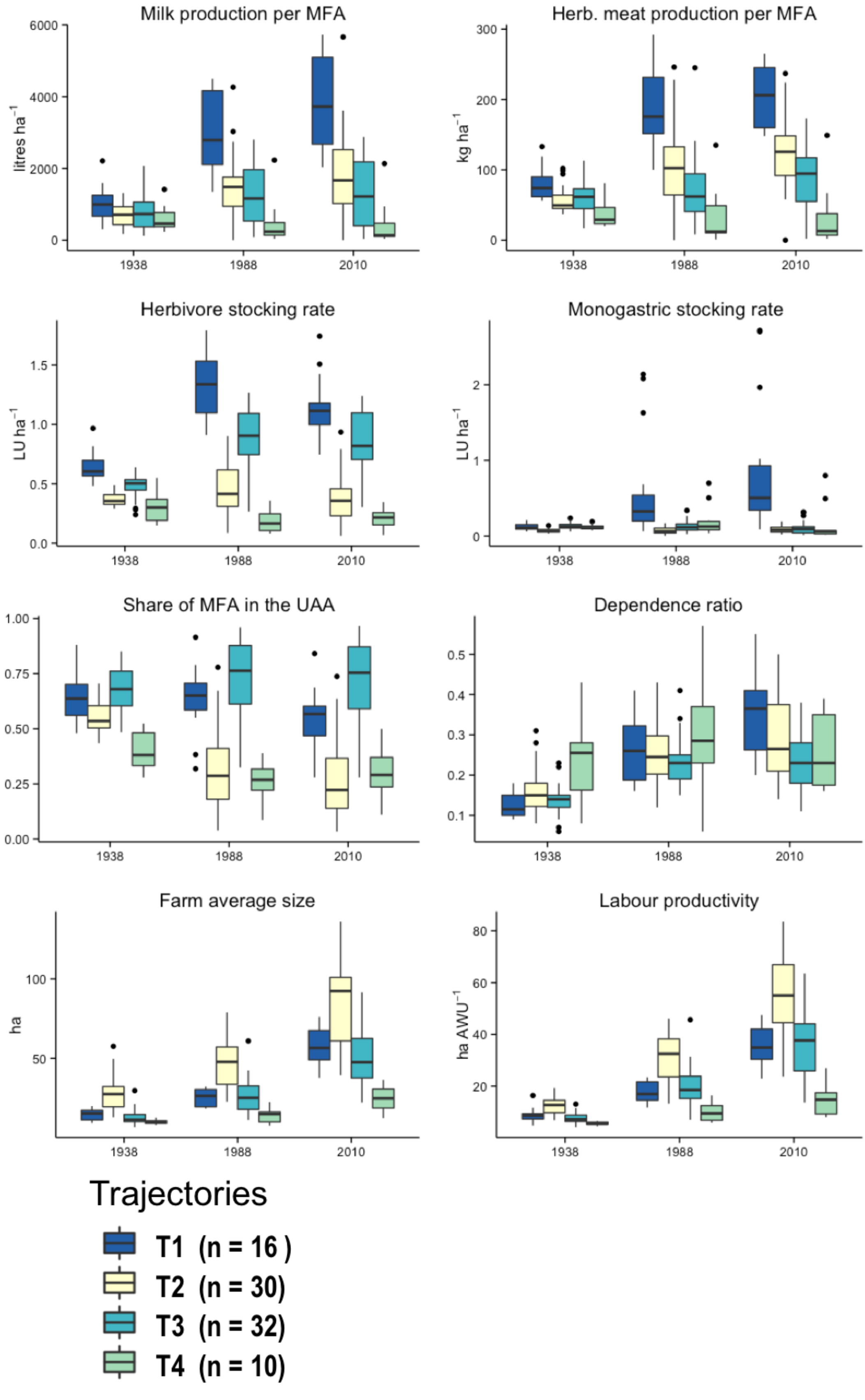

Figure III-5. Trends of change observed in the French departments per type of trajectory. T1, 2, 3, and 4 correspond to 'High intensification of livestock production', 'Crop orientation and intermediate intensification of livestock', 'Grazing orientation of livestock production', and 'Non-livestock dominated' departments, respectively.

2. Exploring spatial patterns of livestock performance and impacts

2.1. Synergies and trade-offs at national level

The patterns emerging from the 48 NUTS3 units revealed six significant synergies (**Figure III-6**) and five trade-offs (**Figure III-7**). Most synergies were convex (**Figure III-6a-d-e-f**) indicating that the joint improvement of pairs of indicators was seldom achieved, and subjected to threshold effects. Three out of five trade-offs were also convex (**Figure III-7a-b-d**) indicating strong antagonism or conflicts among indicators. Two trade-offs were concave suggesting limited antagonisms between the related pairs of indicators.

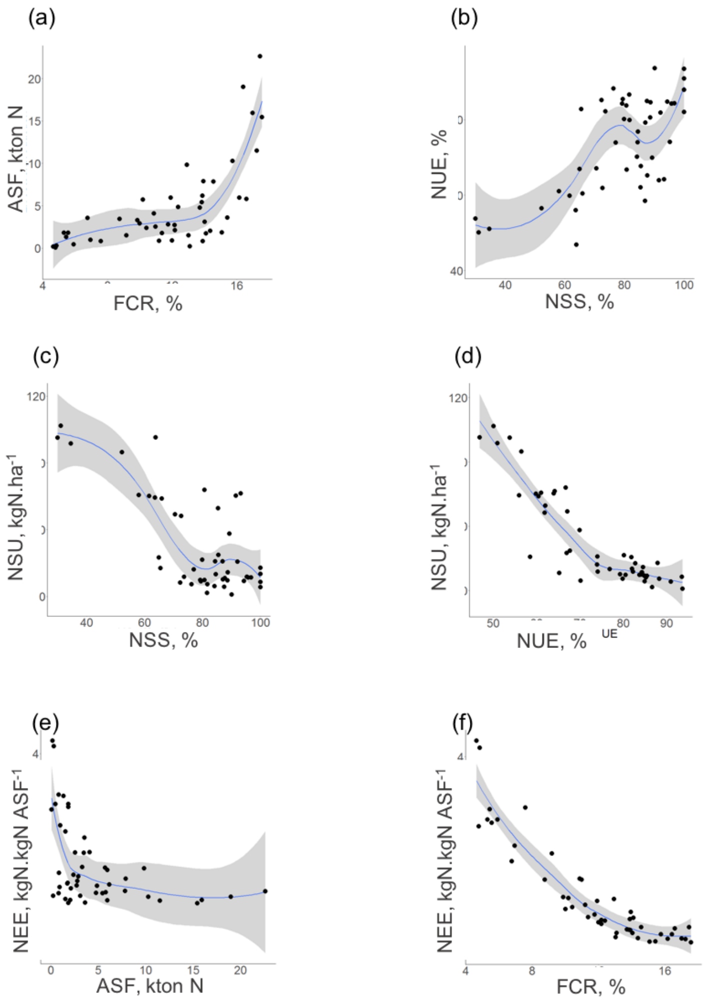

Figure III-6. Synergies among performance (a-b) and among performance and impacts (c-f) in 48 livestock dominated NUTS3 units. ASF: Animal Source Food; FCR: Nitrogen Feed Conversion Ratio; NUE: Fodder Nitrogen Use Efficiency; NSS: Nitrogen Self-Sufficiency; NEE: N Excretion Emissions; NSU: Nitrogen Surplus.

There were two synergies among performance indicators (**Figure III-6a-b**). Animal Source Food (ASF) and the N feed conversion ratio (FCR) had an increasing shape with significant increase of ASF (> 5 kton N) only when N FCR was higher than ~12% (**Figure III-6a**). Fodder Nitrogen Use Efficiency (Fodder NUE) and Nitrogen Self-Sufficiency (NSS) had a polynomial shape whereby higher Fodder NUE (> 80%) was associated with higher levels of NSS (> 80%) (**Figure III-6b**). There were four synergies among performance and impact indicators (**Figure III-6c-f**). N Surplus decreased (at ~20 kgN.ha^{-1}) with higher NSS (~75%) and with higher Fodder NUE (~75%). N Excretion Emissions also decreased (to 1.5 kgN.kgN ASF^{-1}) at varied levels output of ASF (from 5 to 20 kton N) and with higher N FCR (~12%). Distribution of departments was homogeneous (**Figure III-6**).

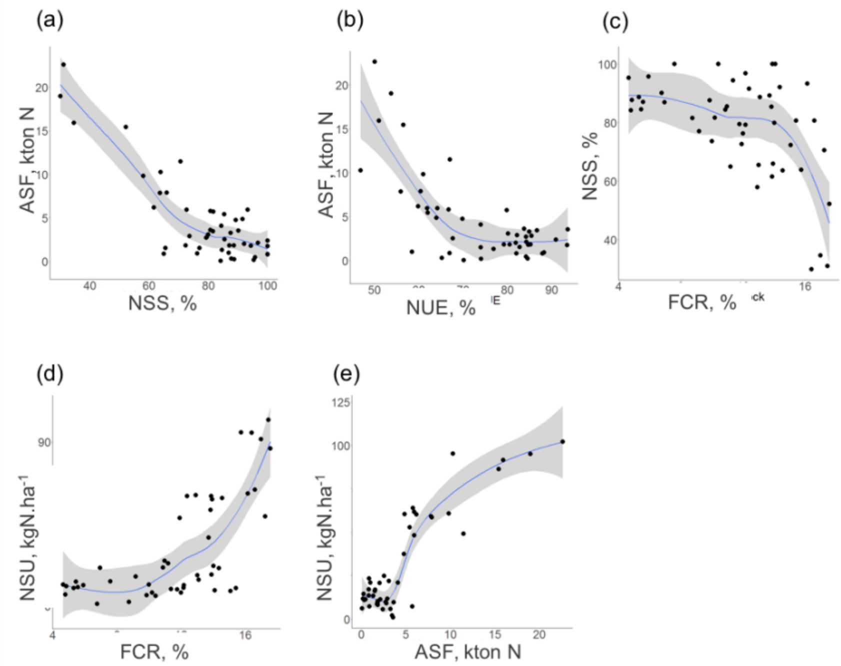

Figure III-7. Tradeoffs among performance (a-c) and among performance and impacts (d-e) in 48 livestock dominated NUTS3 units. ASF: Animal Source Food; FCR: Nitrogen Feed Conversion Ratio; NUE: Fodder Nitrogen Use Efficiency; NSS: Nitrogen Self-Sufficiency; NSU: Nitrogen Surplus.

There were three trade-offs among performance indicators (**Figure III-7a-c**). The relationship between NSS and ASF had a decreasing convex shape and showed that higher output of ASF (> 10 kton N) came at the expense of reduced

NSS (~ < 60%). Fodder NUE and ASF, had a decreasing convex shape and showed decreasing output of ASF (< 10 kton N) with increasing levels of Fodder NUE (> 60%). Distribution of departments along the curve was homogeneous. N FCR and NSS, had a decreasing concave shape and showed that NSS was decreased (> 80%) at increased levels of N FCR (> 14%). Distribution of departments was homogeneous. There were two trade-offs among performance and impact indicators (Figure **III-7**d-e). N Surplus and N FCR had a convex increasing shape showing increased N Surplus (> 30 $kgN.ha^{-1}$) with higher levels of N FCR (> 12%). N Surplus and ASF had an increasing plateau-concave shape and showed rising N Surplus (> 25 $kgN.ha^{-1}$) with growing output of ASF (> 5 kton N). Departments' distribution concentrated at lower levels of N Surplus and ASF.

2.2. The spatial variation of synergies and trade-offs decomposition

Mapping the four quadrants of each bagplot revealed distinct geographical patterns, and allowed to spot regions with better or worse performance and impacts.

Within synergistic relations such as ASF versus N FCR (**Figure III-8a**), regions with 'superior' positioning were mostly identified in the West of France, and better performance was achieved because of higher levels of ASF output at high N FCR, which contributed to lower N Excretion Emissions per output unit (Figure **III-8**e-f). However, these regions showed inferior positioning for the synergies related to lower performance of Fodder NUE and NSS and high N Surplus (**Figure III-8b-c-d**). Conversely, Eastern-Central regions showed superior positioning, because they were mainly dominated by grasslands and had higher levels of Fodder NUE, NSS, thus lower N Surplus.

In trade-offs relations, mapping interactions revealed the marked conflict within pairs of variables, such as N FCR versus NSS, with only a few departments (27%; n= 13) in superior positions (**Figure III-9a**). The conflict was further accentuated in trade-offs between indicators of livestock performance and environmental impact, such as in ASF versus N Surplus, that showed only 10% of superior cases (n=5), which highlighted how unlikely regions are to reach high levels of ASF output without high N Surplus (**Figure III-9e**). The conflict/antagonism in trade-offs was also visible with the high predominance of intermediate positioning in all interactions of **Figure III-9**. Intermediate positioning appeared on average in more than 70% of departements (n= 34), thus showing that gains in one indicator was achieved at the expense of loss on another.

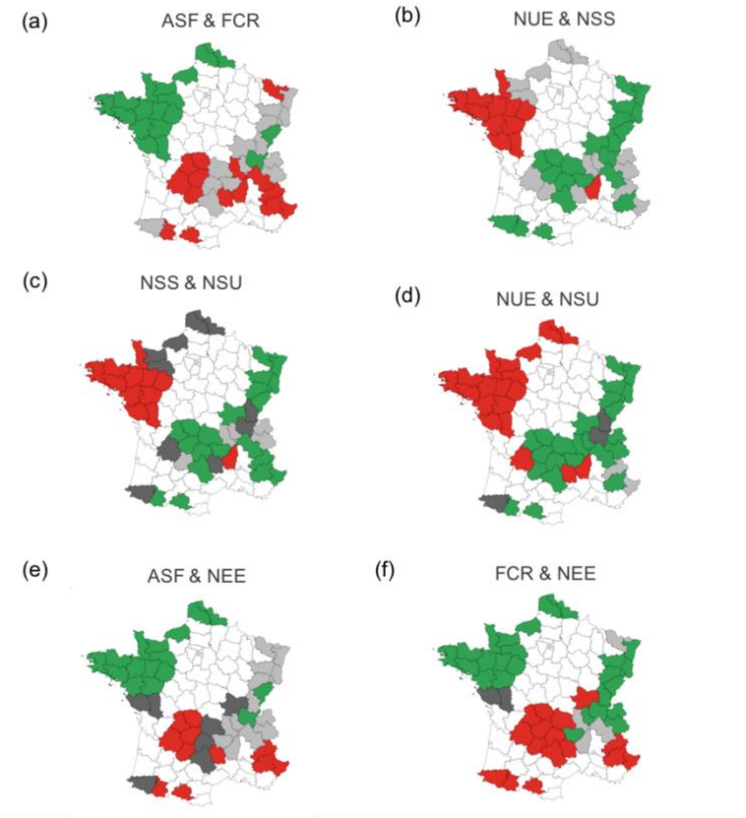

Figure III-8. Spatial decomposition of synergies among performance (a-b) and among performance and impacts (c-f) in 48 livestock dominated NUTS3 units. Green: Superior; Red: Inferior; Grey: Intermediate. ASF: Animal Source Food; FCR: Nitrogen Feed Conversion Ratio; NUE: Fodder Nitrogen Use Efficiency; NSS: Nitrogen Self-Sufficiency; NEE: N Excretion Emissions; NSU: Nitrogen Surplus.

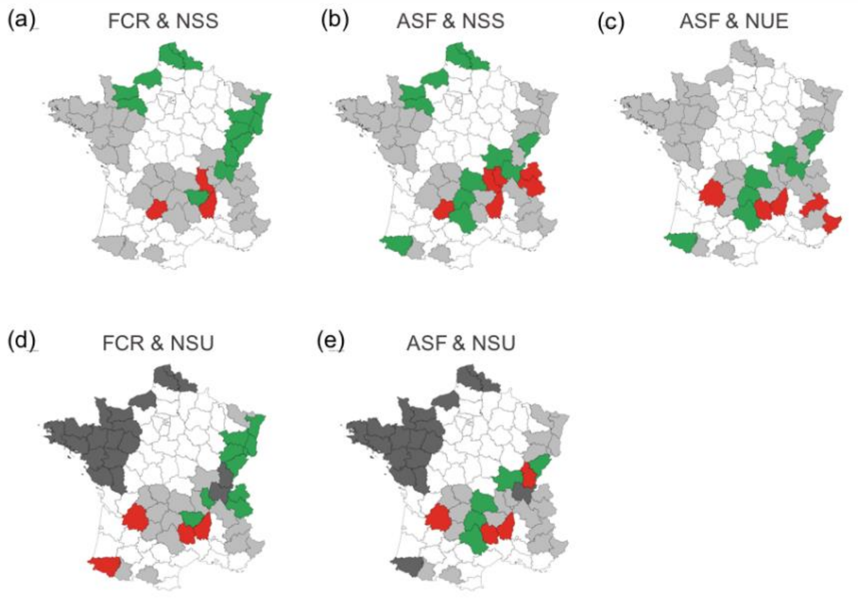

Figure III-9. Spatial decomposition of tradeoffs among performance (a-c) and among performance and impacts (d-e) in 48 livestock dominated NUTS3 units. Green: Superior; Red: Inferior; Grey: Intermediate. ASF: Animal Source Food; FCR: Nitrogen Feed Conversion Ratio; NUE: Fodder Nitrogen Use Efficiency; NSS: Nitrogen Self-Sufficiency; NSU: Nitrogen Surplus.

2.3. Typology of spatial variation of synergies and trade-offs

A principal component analysis (PCA) upon counts of each category (superior, inferior and intermediate positioning of synergies and trade-offs) followed by a hierarchical cluster analysis (HCA) lead four groups of departments.

The PCA resulted in the identification of two factors with an eigenvalue > 1. These factors explained 46.2% and 38.6% of the total variance. Factor 1 was positively related to superior positions of trade-offs and negatively related to inferior positions of synergies. Factor 2 was positively related to inferior positions of trade-offs and mostly negatively related superior positioning of synergies. **Figure III-10** shows the projection of these four classes on the first and second factors of the PCA.

Figure III-11 shows the projection of the classes on a NUTS3 level map of the studied departments of France.

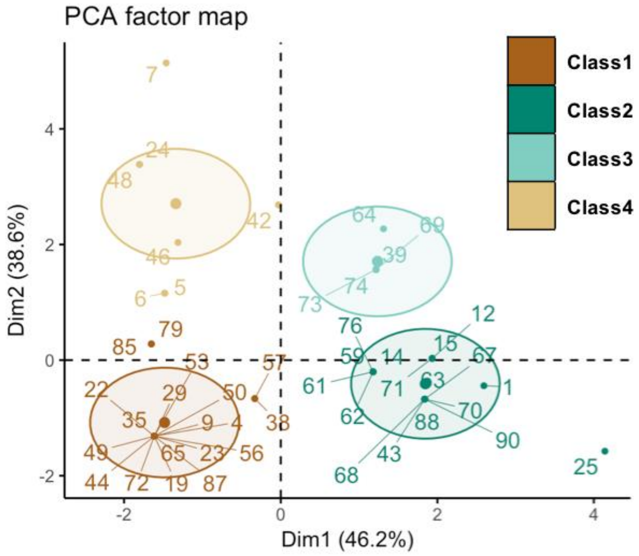

Figure III-10. Projection of four classes on the first and second factors of the PCA.

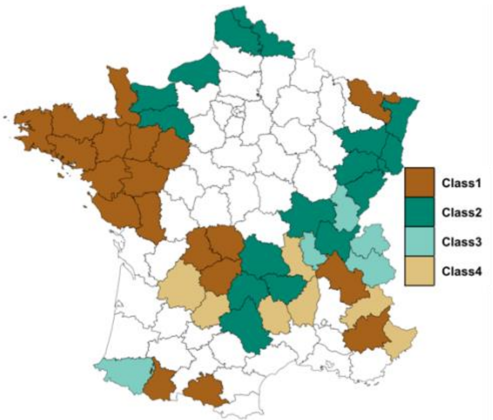

Figure III-11. Projection of four classes, on a NUTS3 level map of France , resulting from HCA upon results of decomposition of synergies and trade-offs.

Class 1 (C1; n = 19) included departments characterised by intermediate positioning in all the cases of trade-offs, which was defined by a high value for one indicator and low value for another indicator. 60% of the departments in C1 were located in Western France and had very intensive livestock production systems, with higher performance in terms of N FCR and ASF but lower performance in NSS and Fodder NUE as well as high impacts associated with large N Surplus. C1 also included departments of the northern border of Massif Central and mountainous regions (French Alps and Pyrenees). These departments were characterized by lower performance in terms of N FCR and ASF but higher performance in NSS and Fodder NUE as well as lower impacts associated with large N Surplus.

Class 2 (C4; n = 14) included departments that were mostly characterised by superior positions in cases of trade-offs. Compared to other classes, departments in C2 also appeared more frequently in superior positions in the synergies studied. These departments were distributed in the North, East and Centre of France. Overall interactions among performance and impacts indicators for C2 ranked higher (performance indicators were higher than for the other classes, and impacts lower) because of higher efficiency of both Fodder NUE and N FCR, and higher levels of NSS along with lower N emissions and N surplus, thus high environmental quality.

Class 3 (C3; n = 5) included departments that were characterised by intermediate positioning in most of the cases of synergies, which was defined by high value for one indicator and low value for another. Compared to other classes, departments in C3 also appeared less frequently in inferior positions in all synergies studied. Intermediate positioning were mainly characterised by a combination of good performance in impact indicators and Fodder NUE, N FCR along with poor performance in NSS and ASF indicators.

Class 4 (C2; n = 7) included departments that were mainly characterised by inferior positions in cases of trade-offs, which was defined by low values for both indicators of the interaction. Compared those of the other classes, departments in C4 also appeared more frequently in inferior positions for all the synergies studied. Overall interactions among performance and impacts indicators for C4 departments were ranked very low because of marginal livestock production, with low efficiency rates along with poor environmental quality.

3. Linking provision of services to past intensification trajectories

According to the Kaiser criterion (eigenvalue > 1) two axis of the co-inertia analysis were kept, which explained 93% of the total variance. the Monte Carlo test revealed a high degree of co-structure between the two tables (RV coefficient = 0.57; p-value < 0.05) suggesting a relationship between intensification trajectories and services provisioning.

The high degree of co-structure resulted from a number of correlations between variables in the two tables (**Table III-2**). Moderate to strong correlations occurred 17 times out of 90 correlations (10 variables in table 1 times 9 variables in table 2). Ten correlations referred to livestock related variables:

- The provision of heritage landscapes (Landscape) and employment on livestock farms (Emp Farm) was positively correlated with Herbivore stocking rate.

- the provision of employment at both farm and agro-food industry (Emp Farm; Emp Ind) were positively correlated to Monogastric stocking rate and Milk productivity; although it was observed negative correlation between water quality (Water) and Monogastric stocking rate and Milk productivity.

- The provision of high nature value areas (HNV) and water quality was negatively correlated Herbivore meat productivity.

Five correlations referred to land use related variables. The share of the fodder area was positively correlated to the provision of heritage landscapes, conservation of biodiversity, water quality and the contribution of livestock to employment (Employ). It showed strong correlation with high nature value areas. Two correlations referred to socioeconomic variables. The dependence ratio (i.e. inverse of self-sufficiency) was positively correlated to the provision of employment in livestock farms and in the agro-food industry.

Table III-2. Correlation coefficients between intensification and services provisioning variables from French departments.

		Cultural			Environmental			Rural vitality		
		Agrotourism	Landscape	Product	Biodiversity	HNV	Water	Employ	Emp Farm	Emp Ind
Livestock	Herbivore SR	-0.01	**0.68**	0.19	0.36	0.28	0.23	0.46	**0.52**	0.09
	Monogastric SR	-0.26	0.02	-0.42	-0.25	-0.43	**-0.57**	0.25	**0.52**	**0.78**
	Meat productivity	-0.26	-0.23	-0.02	-0.45	**-0.59**	**-0.58**	-0.12	0.13	0.38
	Milk productivity	-0.22	0.03	-0.41	-0.16	-0.49	**-0.58**	0.24	**0.53**	**0.70**
Land use	Share of UAA	-0.25	-0.02	0.11	-0.10	-0.31	-0.24	0.38	0.06	-0.09
	Fodder area : UAA	0.24	**0.64**	0.06	**0.59**	**0.71**	**0.56**	**0.50**	0.44	-0.04
Socioeconomic	Average farm size	-0.20	0.08	0.20	-0.00	0.02	-0.03	0.08	0.11	0.20
	Labour productivity	-0.13	0.01	0.09	0.11	0.14	0.18	0.06	-0.14	-0.14
	Dependence ratio	-0.17	0.30	-0.09	-0.19	-0.18	-0.32	0.22	**0.50**	**0.57**
	Tractors density	-0.14	0.38	-0.07	0.23	0.06	0.06	0.39	0.42	0.34

Agrotourism: Proportion of farms practising agrotourism; Landscape: Areas in heritage landscapes (grassland, specific areas, and trees); Product: Number of quality-labelled animal products (SIQO); Biodiv: Proportion of grassland birds in bird community; HNV: Area classified as High Nature Value per km^2; Water: Proportion of municipalities outside nitrate vulnerable zones; Employ: Contribution of livestock sector to overall employment; EmpFarm: Workforce on livestock farms; EmpInd: Employees in livestock agrofood industry

Figure III-12 shows plots derived from co-inertia analysis on the two data sets of intensification and services provisioning variables. **Figure III-12a** shows the variables that had higher correlation with these two axes. First axis was positively correlated with monogastric stocking (Mon SR) rate and milk productivity (Milk prod), and negatively correlated with environmental variables (Water, HVN, Biodiv). Second axis was negatively correlated to the share of fodder area (MFA:UAA) and herbivore stocking rate (Herb SR), and to the provision of employment in livestock farms (Emp farm), the contribution of livestock to overall employment (Employ) and to the provision of heritage landscapes (Landscapes). **Figure III-12b** illustrates the French departments plotted in these two axes. The hierarchical cluster analysis revealed three groups (**Figure III-12c**) which are projected on a NUTS3 map of France (**Figure III-12d**).

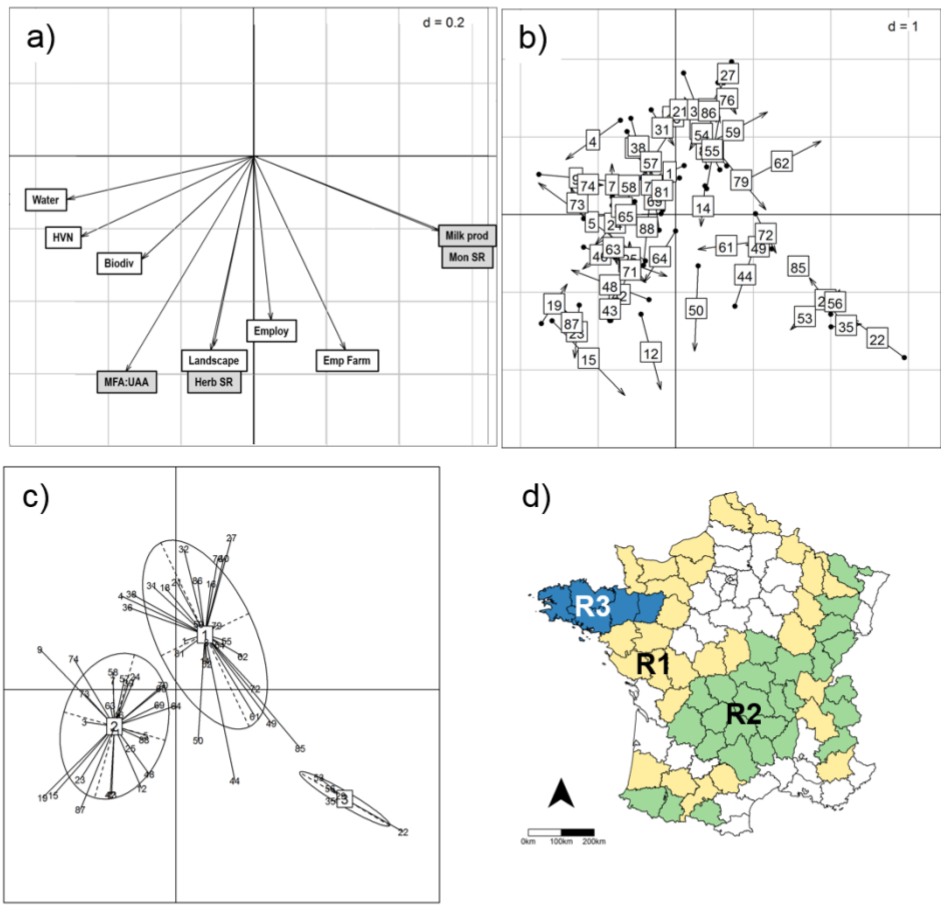

Figure III-12. Co-inertia analysis results followed by classification. a) Projection of intensification and services provisioning variables most correlated with co-inertia analysis axis 1 and axis 2. b) Projection of French departments scores after co-inertia analysis. Boxes filled in grey color are related to intensification variables and boxes filled in white color are related to services' variables. c) Projection of the three groups on the first and second axes of the co-inertia analysis after the hierarchical cluster analysis. d)

Location of the three groups of French departments. R1, R2 and R3 correspond to 'Mixed-crop livestock areas', 'Extensive livestock areas' and 'Intensive livestock areas', respectively.

Table III-3 presents the absolute values of variables and the % rate of change.

Table III-3. Trends of change in the French departments per group: 'Mixed-crop livestock areas', 'Extensive livestock areas' and 'Intensive livestock areas'.

Variables	Year	Mixed crop-livestock areas n = 28	Extensive livestock areas n = 27	Intensive livestock areas' n = 5	Average n = 60
Herbivore SR	1938	0.49 b	0.48 b	0.68 a	0.50
	2010	0.72 c	0.93 b	1.28 a	0.86
	% change	48%	95%	89%	73%
Monogastric SR	1938	0.10 b	0.13 ab	0.16 a	0.12
	2010	0.24 b	0.09 b	1.80 a	0.30
	% change	149%	-28%	1045%	160%
Meat productivity	1938	64 a	63 a	74 a	65
	2010	158 a	86 b	201 a	129
	% change	145%	36%	171%	100%
Milk productivity	1938	778 a	628 a	907 a	721
	2010	2142 b	1168 c	5000 a	1942
	% change	175%	86%	451%	169%
Share of UAA	1938	65% a	52% b	73% a	60%
	2010	57% a	43% b	63% a	51%
	% change	-12%	-17%	-14%	-14%
Share of fodder area	1938	63% a	68% a	59% a	65%
	2010	43% b	77% a	59% b	60%
	% change	-32%	13%	0%	-8%
Average farm size	1938	19 a	14 b	12 b	16
	2010	72 a	56 b	48 b	63
	% change	272%	295%	315%	284%
Labour productivity	1938	11 a	08 b	07 b	9
	2010	48 a	41 ab	30 b	43
	% change	348%	396%	341%	367%
Dependence ratio	1938	0.14 a	0.14 a	0.15 a	0.14
	2010	0.26 b	0.23 b	0.44 a	0.26
	% change	84%	65%	199%	86%
Mechanisation *100	1938	0.11 a	0.06 b	0.03 b	0.08
	2010	0.48 a	0.55 a	0.60 a	0.52
	% change	341%	784%	1881%	540%

Means followed by same letter within a row do not significantly differ by Tukey's test (P<0.05). Indicators are expressed as the mean of all departments belonging to each group.

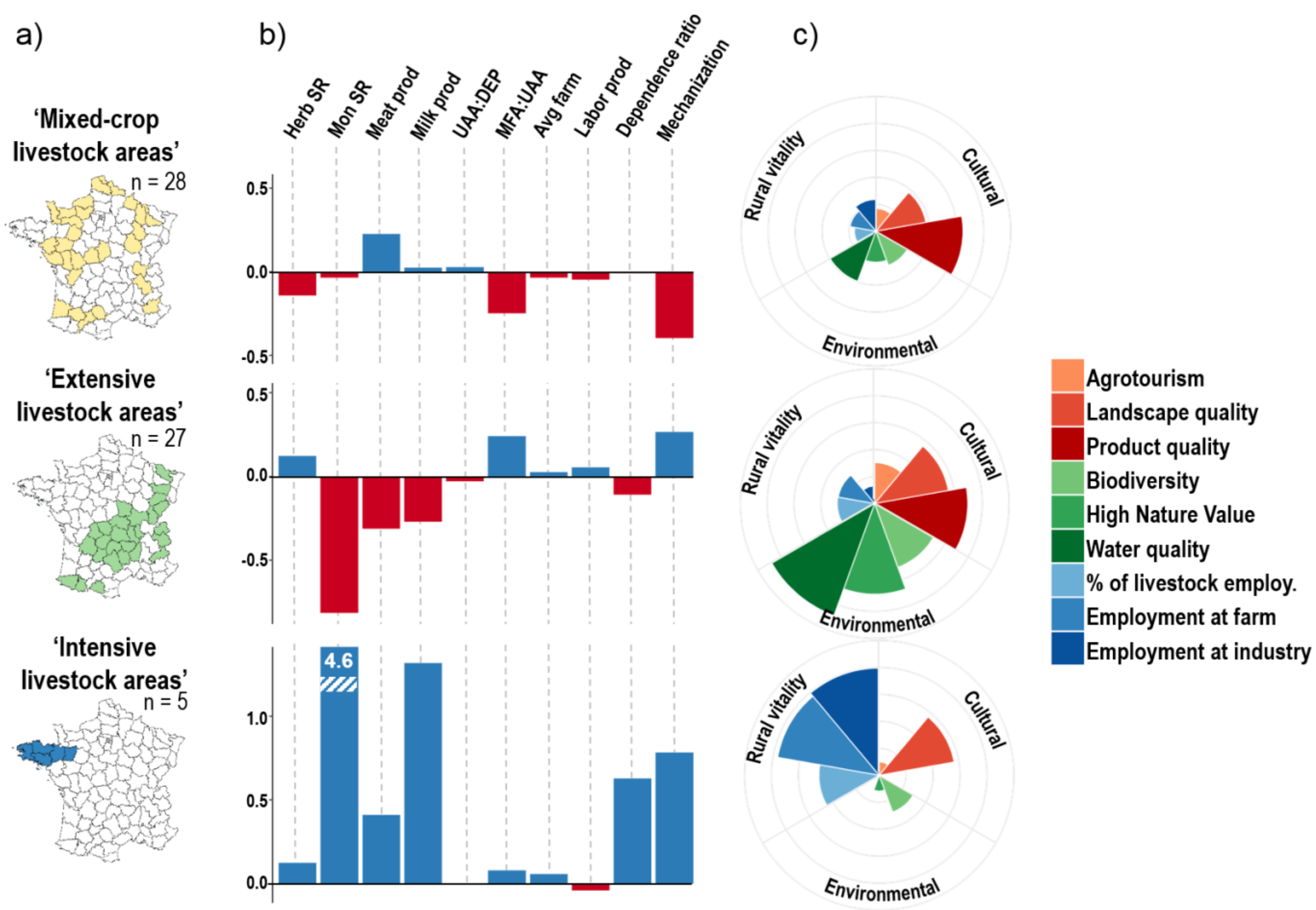

Figure III-13. Spatial trends of change in intensification variables and current provisioning of services. a) Location of the three groups of French departments, 'Mixed-crop livestock areas', 'Extensive livestock areas' and 'Intensive livestock areas'. b) Average rate of change of intensification variables in three groups of French departments (blue bars indicate the rate of change was higher than in an average department and red bars indicate the rate of change was higher than in an average department and red bars indicate it was lower). c) Average provision of services per group of French departments.

Figure III-13 displays bar charts illustrating the rate of change for intensification variables per group of departments, and polar charts showing the corresponding bundle[5] of services provided in each group.

‘Mixed-crop livestock areas’ (R1; n = 28) mainly included departments located on the surrounding area of the Paris basin and few in the South-West and South-East of France, and was characterized by smooth rates of change (**Table III-3**). Compared to an average department, R1 departments had lower rates of change of herbivore stocking rate (48%), and share of the fodder area (-32%) and of mechanization (341%). R1 had similar rate of change of an average department for monogastric stocking rate (149%), milk productivity (175%), share of utilized agricultural area (-12%), average farm size (272%), labour productivity (348%) and dependence ratio (84%). The only variable that had considerably higher rate of change compared to an average department was the herbivore meat productivity (145%). The provision of services showed low levels of all types of services, except for heritage animal products. The fact that this group has passed through smooth changes in the process of intensification, explains the minor provision of services by the livestock sector. The geographical proximity with crop specialized departments on the North and with departments emphasizing grazing on R2, characterizes a transition frontier where livestock loses importance, either in aspects of lower stocking rates of animals, and retraction of main fodder area.

‘Extensive livestock areas’ (R2; n = 27) mainly included departments located in the French Massif Central and in the East, and was characterized by contrasted rates of change. Compared to an average department, R2 departments had lower rates of change meat productivity (36%), milk productivity (86%), and in the dependence ratio (65%). The decreased monogastric stocking rate (-28%) was markedly opposed to the average increase rate observed in all departments. R2 had similar rate of change of an average department for share of utilized agricultural area (-17%), the average farm size (295%) and the labour productivity (396%). R2 presented rates of change considerably higher compared to an average department for herbivore stocking rate (95%), the share of the

[5] Raudsepp-hearne et al. (2010) defines a bundle of services as sets of ecosystem services that repeatedly appear together across space or time.

fodder area (13%) and mechanization (784%). The provision of services showed the most balanced pattern of services compared to other groups. Although low levels of vitality services were observed, cultural and environmental services were provided at the highest levels among groups. Increased rates of changes favoring herbivores over monogastrics, along with increased share of the main fodder area have played an important role on environmental services. Although R2 had lower levels of meat and milk productivity compared to other groups, it had the highest level of heritage animal products, which in this case indicates that quality compensate for quantity of animal products. R2 also showed high levels of heritage landscape and the highest level of farms practicing agrotourism.

'Intensive livestock areas' (R3; n = 5) included Western French departments, and were characterized by the highest rates of change. Compared to an average department, R3 departments had slightly higher rates of change in herbivore stocking rate (89%), share of fodder area (0%) and average farm size (315%). Nevertheless, this rates of change were minor compared to marked increased rates of change in monogastric stocking rate (1045%), meat productivity (171%), milk productivity (451%), dependence ratio (199%) and mechanization (1881%). In this group, all livestock related variables had higher rates of change compared to an average department. R3 had similar rate of change of an average department in the share of the agricultural area (-14%) and labour productivity (341%). The provision of services was mainly characterized by high levels in the vitality services (related to employment), and to a lesser extent to the provision of heritage landscapes. Environmental and remaining cultural services showed very low levels, notably for the provision of water quality and heritage animal products. The higher rates of change in the intensification process, specifically monogastric stocking rate and milk productivity, allowed the development of livestock sector in these departments, contributing to large employment opportunities. However, the concentration of very intensive production systems, at high stocking rates, and increased dependence ratio (purchased feed) lead to manure management issues, thus overall depleted environmental quality.

IV. DISCUSSION

1. Results highlights

Our first analysis revealed that the intensification of the French livestock sector was spatially differentiated and involved four different types of trajectories. Type 1 and type 3 trajectories were characterized by a gradient in the intensification and specialization ranging from intensive monogastric/herbivore to extensive specialized herbivore production. The type 2 trajectory represented a specialisation towards crop production while maintaining a limited number of herbivores at an intermediate meat and milk production level. The type 4 trajectory exhibited the lowest livestock population and productivity levels.

Our second analysis revealed how livestock configuration influenced regional performance in terms of resource use and impacts to the environment. Synergistic relationships were observed in two groups of variables: *i)* between Fodder NUE, and N Self-sufficiency, and N Surplus, and *ii)* between N Feed conversion ratio, and Animal source food, and N Excretion emissions. Conflicting relationships were characterized by gains in N Feed conversion ratio, and Animal source food on detriment of Fodder NUE, N Self-sufficiency, and N Surplus. The decomposition and mapping of synergies and trade-offs followed by mapping showed that efforts made in one direction, for instance on gains in efficiency and economies of scale, often compromised other dimensions, e.g. through increased environmental impacts. Most high-performance regions, in terms of the six indicators studied, were characterized by a larger share of ruminants over monogastrics, with an emphasis on dairy production on grassland-based at moderate levels of stocking rate.

Our third analysis revealed that the provision of social, cultural and environmental services was spatially structured and based on three groups, determined by different rates of change in intensification variables over time. Mixed crop-livestock areas were mainly defined by smooth changes, with close variation to national averages, which resulted in low provision of services. Extensive livestock areas were mainly defined by higher rates of change on variables related to specialization on grazing (herbivores and fodder area), and lower rates of change on productivity aspects. This contributed to provision of high levels of environmental and cultural services, such biodiversity conservation and product quality labels. Intensive livestock areas were mainly defined by high rates of change related to the intensification of livestock production – high stocking rates and productivity, which contributed to of high levels of vitality services, such as high employability in both farm and industry.

The three studies combined together achieved the goal of the PhD, which was “to develop a holistic assessment of livestock areas using multi-metric indicators encompassing positive and negative contributions”. Main findings can be summarized as follows:

Past intensification trajectories determined the current heterogeneity of livestock production. This heterogeneity generated different levels of performance and impacts. Regions following a path of intensification in livestock production played a positive role on progresses regarding food provisioning and employment. However, these regions displayed conflicts as high levels of production came at the cost of poor environmental quality, a loss of self-sufficiency and a limited provision of cultural services. Regions following grassland-based trajectory achieved lower levels of food provisioning. Lower food production was however compensated for by higher quality products, along with an increasing role on biodiversity conservation, high nature value of land and high water quality.

2. The most important factors influencing the process of intensification

At national level the most influencing factors of the intensification process were related to socioeconomic variables, with mechanization, labor productivity and farm enlargement scoring higher changes between 1938 and 2010. This changes nevertheless had similar rate of change throughout the country, and did not play an important role on the differentiation of trajectories at department level. Factors that primarily influenced the differentiation of trajectories at department level were related to changes in livestock variables, such as species stocking rates and productivity, and land use related changes in the main fodder area. Varied levels of changes in these latter variables enabled the characterization of four distinct trajectories.

The four trajectories were spatially structured and revealed that intensification process occurred in very different ways across France. It showed a gradient of regions where *i)* livestock became marginal; where *ii)* livestock emphasized extensive production; where *iii)* livestock was replaced by crop specialization but also kept mixed crop-livestock systems at the margin and where *iv)* livestock emphasized intensive production, characterized by overstocking with land carrying capacity largely exceeded.

The spatial heterogeneity of livestock is a result of dual changes in: land cover, mostly characterized by expansion of arable land at the expense of grasslands contraction; and in land use intensity, mainly defined by changes in productivity and stocking rates (Thornton, 2010). These changes reflected the separation between crop and livestock production areas. The biophysical drivers determined the direction of change, with the development of crops on plains, and the emphasis on grazing in marginal and mountainous land. Such findings corroborates with prior reports of Chatzimpiros and Barles (2010) that links land use specialization to factors such as agronomic potential and farm size, and points to the gradual encroachment of crops over grasslands in the Paris basin (Northern France) over time, and to the major development of the livestock sector in Western France. Socioeconomic drivers also played a role, with higher workforce availability determining farming orientation towards livestock, and towards crop production in the alternative case. This corroborates with findings reported by Gambino (2014), regarding the development of intensive livestock production in Western France’s departments.

Increased production per main fodder area of livestock reflected gains in productivity, thanks to the adoption of technological packages, such as improved nutrition, genetics and management (de Vries and de Boer, 2010). However these gains need to be balanced against an increasing dependence on external resources, which was significant in some regions. In the trajectory of high intensification of livestock production, the dependence ratio variable (feed costs relative to the output) have almost tripled between 1938 and 2010. Although productivity levels increased, land displacement effects could have compensated for the apparent gains. Prior studies about cattle production in Western France also reported on this trend, showing that land requirements for feed production were somewhat externalized (Ross et al., 2017).

The analytical procedures we applied to study the intensification process provided additional insight into the general dynamics and the interplay of factors leading to the current heterogeneous state of the French livestock sector. The choice of the method, in addition to an extended time frame running from 1938 to 2010, represented an advance compared to prior studies, which usually constructed typologies upon an instantaneous basis (Le Noë et al., 2017). We could, therefore, quantify and rank the main changes in livestock production while providing a dynamic view and a long-term perspective over a period in which the socioeconomic context drastically changed. This knowledge and vision is essential to managing livestock farming systems, whether to maintain desirable aspects of intensification or to mitigate potentially negative impacts (Darnhofer et al., 2010). Our level of analysis, the department, enabled us to approaching the sustainability question from a new perspective. Sustainability at farm level is necessary but it is not a sufficient condition for achieving overall sustainability, as one farm in isolation does not determine the regional sustainability.

In this study, the choice of the department level and the use of an extended period of time spanning 72 years enabled a dynamic view of the intensification process and patterns of change within the livestock sector in France. Nonetheless, a finer-level analysis might reveal additional heterogeneity within the department level (Teillard et al. 2012). There is clearly a trade-off between assessing the process of intensification at a more aggregated level or at a finer resolution. On one hand, opting for the department level offered the advantage of a significant body of available data, and enabled a macro analysis covering a very large mixture of biophysical conditions. Conversely, a farm level analysis could provide a deeper understanding of the intensification process (Chantre and Cardona, 2014), although the area would be limited, the process would be more time and resource-consuming, the costs would be higher (time and money), and the accuracy would be both questionable and limited, as indicated by Ryschawy et al. (2013) about retrospective interviews.

Our typology could be used to support decision-making at the regional level as it provides a spatially-differentiated assessment of the process of intensification in the livestock production sector. This typology would be valuable for studying the impacts of CAP reforms on livestock concentration and species balance (herbivores: monogastrics) and on the land use ratio (crop: grassland), as reported by Veysset et al. (2005).

From a policy-making perspective, our typology could shed light on the transition of livestock farming systems. Based on quantitative data of changes that occurred over the past 70 years, the different trajectories revealed that intensification was a spatially differentiated phenomenon, suggesting that transitions will not occur in a homogeneous fashion. Further, our typology could serve as a tool for choosing differing regions in terms of livestock intensification (Beudou et al. 2017). Finally, the different trajectories suggest the need for several strategies tailored to different contexts in the agroecological transition of livestock production.

3. How different configurations of livestock influence performance and impacts across areas?

The analysis of synergies between performance indicators and environmental impacts pointed to two major conclusions. Reduced local environmental impact (N surplus) was achieved with high levels of self-sufficiency and fodder NUE; and reduced global environment impact (emissions) was achieved at high livestock productivity levels. Nevertheless, the analysis of trade-offs showed that regions having high livestock productivity levels were often characterized by poor self-sufficiency, fodder NUE and local environmental quality.

Therefore, the overall performance of a given region is dependent on the type of performance and impact variables under scope. The spatial analysis was marked by heterogeneous patterns as a result of above described synergies and trade-offs. However, the decomposition of interactions and mapping of spatial patterns revealed that beyond the general trends some regions did manage to conciliate on average high performance for all indicators studied.

The heterogeneous spatial differentiation is linked to the diversity of livestock systems present in the departments studied. The set of 48 departments selected for this analysis was based on a criterion of past intensification trajectories. In a first moment, this roughly explains the overall performance of departments following an intensification trajectory, mainly characterized by intermediate positioning, as gains in production performance were often traded-off with local environmental issues and the loss of self-sufficiency. If departments pertaining to the intensification trajectory had homogenous pattern of performance and impacts, departments that followed a grazing orientation trajectory were much more heterogeneous.

Trajectories characteristics provide some background knowledge on performance and impacts, though it does not suffice to explain the heterogeneity across regions. Characteristics such as species composition, production objective, stocking rate and land use types help further explaining the reason of high spatial heterogeneity. Departments specializing in intensive production systems had higher performance in terms of feed conversion efficiency and provision of ASF, mainly because of higher share of monogastrics and dairy production. However, these departments had higher dependency on global feed protein, and raised environmental concerns due to the large amounts of manure generated by landless systems with a limited agricultural area available for spreading. Departments located in marginal and mountainous areas have mainly emphasized grazing in the past trajectory, but at different levels of production objective (milk:meat). Departments with higher production of milk over meat, presented overall better performance. This results from a combination of factors, among which dairy cows higher feed conversion efficiency compared to beef, thus lower emissions (Dettenmaier et al., 2017). It also highlights dairy systems reduced dependency on concentrates compared to monogastrics, and consequently higher self-sufficiency.

The higher heterogeneity observed also reflects the variety of issues covered by our selected indicators. Most studies on livestock environmental impacts used approaches whether from a product- or land-based perspective, but not both at once. Our study represents an advance as it reveals that these two indicators are in synergistic relationships with distinct groups of indicators:

- land-based: synergy between NSU and NUE-NSS;
- product-based: synergy between NEE and FCR-ASF;

that, in turn, are in conflicting relationship among each other (NUE-NSS and FCR-ASF). The question of the functional unit to which environmental impact are referred had been seldom treated in literature. A recent study focused on dairy farms (Dettenmaier et al., 2017) corroborate to our findings, and reports changing environmental impacts with different functional units. The self-sufficiency indicator also allows a view that goes beyond our direct measures of environmental impacts, as it represents the level of dependence on external feed resources, thus an indirect measure of potential land displacement - which is also related to environmental impact (Meyfroidt et al., 2010).

The novel approach we proposed to assess performance and impact in livestock areas, by selecting indicators from a material flow analysis, then characterizing types of interactions, and decomposing the existing spatial heterogeneity at department level, has brought new knowledge for livestock sustainability thinking. Our analysis revealed how livestock sector configuration influenced overall regional performance in the use of resources and impact to the environment. Most promising configuration characteristics, in terms of the six indicators we studied, suggested i) regions favouring a larger share of ruminants over monogastrics, ii) grassland-based dairy production. The use of viability theory[6] (Aubin, 2009) could enable to identify the safe operating space of livestock areas, by defining thresholds on multiple performance and environmental impacts. It would consist in navigating through livestock areas by fine-tuning *i)* species composition, *ii)* stocking rates and *iii)* production objectives, in order to maintain livestock areas within viable limits. In the case of Brittany this could shed light on leverage points for achieving more sustainable patterns of production.

The question of performance and impact in livestock production have been addressed in several studies, mainly focusing dairy production, very often treated at animal and/or farm level (Iribarren et al., 2011; Zehetmeier et al., 2012; Shortall and Barnes, 2013; Mu et al., 2017). We believe this thesis starts building an

[6] http://www.sad.inra.fr/en/All-the-news/Theorie-Viabilite

answer for issues on sustainable livestock production, encompassing the four main reared species (cattle, small ruminants, poultry and pig), as it draws from an assessment based on real production cases, showing different patterns of regional performance. This provides knowledge (or a basis) for future research/action on the possibilities of re-configuration of drivers of performance, in order to steer regions towards optimal levels of efficiency in the use of resources and reduced environmental impacts.

4. To what extent social, environmental and cultural services provided by livestock are linked to past intensification trajectories?

The process of intensification played an essential role on the differentiation of livestock areas in terms of provision of social, environmental and cultural services. Changes in livestock productivity were the main positive determinants of rural vitality. But changes in livestock productivity influenced negatively the provision of environmental services. Changes in the fodder area influenced to a large extent the provision of environmental services, played a role in heritage landscapes, and had a positive contribution relative to overall employment. Although socioeconomic changes were very marked in absolute terms, they did not influence in a clear way the provision of services; with exception to changes in dependence ratio that went together with employment in farm and industry.

As changes in the intensification process were spatially differentiated, the current provision of services by the livestock sector also reflected the heterogeneous patterns of change. The three groups identified showed that regional differentiation patterns in the intensification- determined by different drivers, contributed to the formation of three distinct bundles.

Biophysical drivers determined significant changes in land use cover, characterized by the conversion of grasslands into cropland in the plains (‘Mixed crop-livestock areas’). In areas where such change was not possible because of limited agronomic potential (marginal and mountainous areas), the alternative consisted on emphasizing on grazing, as observed in the ‘Extensive livestock areas’ (Massif Central and Eastern France). The prominence of grazing systems, marked by lower stocking rates and lower productivity levels, influenced the provision of services in a more equilibrated pattern. The maintenance of grasslands played essential role in the conservation of biodiversity, as it supported higher share of birds that depend on this type of habitat to complete their life cycle (Henle et al., 2008). Teillard et al. (2017) highlight that increased biodiversity is achieved with optimal extensification, thus corroborating to our findings concerning the role of grasslands habitats in maintaining diverse and particular adapted species. It also influenced water quality as grasslands provides continuous soil surface cover, and when managed at low levels of inputs and stocking rates, has positive contribution to water filtering (Hooda et al., 2000).

The specialization in 'Intensive livestock areas' were possible thanks to initial orientation of livestock production and because of higher share of rural population in 1938, thus high availability of workforce (Gambino, 2014). The monogastric population surged and lead to increased stocking rates, about a 1045% change over the period, which contributed to the development of employments in the livestock sector. There was an important movement of modernization in these areas (Brittany) based on technological rationalism and collective development. It enabled increased productivity and were followed by the development of upstream and downstream supply chain, i.e. feed and food industry (A. Lang et al., 2015). If this advances contributed to high levels of rural vitality services, it also had a negative impact on the environment. The large number of monogastrics along with dairy cows kept in landless systems is certainly the main driver of increased livestock productivity, that was essential in terms of high provision of ASF, but created issues related to manure management. Increasing quantities of manure in a limited area for spreading resulted in over fertilization of agricultural areas with consequent high losses to water streams, thus depleting water quality.

5. Added-value and limitations

Our combined approach proposed a new way of looking to livestock production, taking a retrospective dynamic to understand the current state, organization and functioning of systems. We provide novel insights on the sustainability assessment of livestock production, by exploring dimensions so far less studied, such as socio-economic and cultural. The framework adopted attribute to livestock a direct account on the use and transformation of resources, whether by its direct impact through consumption of feed and production of manure, or by the provision of goods and services to the society. During our analysis we sought for a balance between dimensions and themes of sustainability, and proposed a multi-metric set of indicators to account for spatial patterns of trade-offs between livestock production and the environment.

Although we sought for representing in the most comprehensive way the intensification trajectories of livestock production from 1938 to 2010, one could argue that it missed accounts of economic variables (e.g. input costs, output prices) or policy measures. Although this could complement our findings, this was not the direction we choose because these data were not available from 1938 through 2010, in particular market prices, either due to the lack of a market for some products or a record of the market that was long enough. We believe nevertheless, that our findings – based on quantitative data of changes in intensification variables in the past 70 years, provides a valuable view on leverage points towards more sustainable livestock production.

Regarding the analysis of synergies and trade-offs, our contribution rely on the account of livestock impacts taking a land-based approach, as well as the account of the regional self-sufficiency, which so far had little attention on literature. The self-sufficiency indicator is a valuable measure of the capacity of a given area to meet livestock feed demand on local resources. It also enabled to detect areas where livestock was overstocked and reduced local feed availability was compensated with large imports on protein. In these areas, the self-sufficiency indicator revealed the link between overstocking and local environmental impacts. In addition to computing for self-sufficiency in terms of feed protein availability/imports, it would be desirable in the future to include the land displacement resulting from protein trade (Meyfroidt et al., 2010). Besides, the feed/food competition debate gained importance and could consist in another component of trade-off, as livestock production in the developed world – ruminants to a less extent than monogastrics, relies largely on human-edible proteins as feed (Mottet et al., 2017). This would add a fourth dimension to the original three of the sustainability concept, which consists on the ethics of feeding livestock with human-edible foods (Makkar and Ankers, 2014). Additionally, a sensitivity analysis could provide a view into the most important input parameters of the nitrogen metabolism that influences the output variance (Groen et al., 2016, 2017). It could therefore, be a valuable asset to complement our findings and to point to uncertainty because of spatial variability or variability of coefficients from different sources.

The analysis regarding the influence of the intensification process in the provision of services by the livestock sector delivered the last piece to meet our goal, to assess the overall contribution of livestock in terms of performance and impacts. Although we could link past changes in different types of drivers to the different levels of services, we acknowledge some types of services lacked a more extensive range of indicators. The rural vitality services indicators reflect this weakness, as it fails to account for aspects related to the multifunctionality of livestock production in extensive systems (Weiler et al., 2014). Yet, further insights could be gained if more attention is placed on records of livestock contribution to indirect employment, local and social networking and social life (Ryschawy et al., 2017). Therefore, future research should integrate such aspects so far neglected or under-represented, in view of valuating goods and services provided in extensive and pastoral areas.

Concerning the level of our analyses, the department (NUTS3), it strengthened understanding of livestock production issues at an intermediate level compared to most studies, which are farm and global levels. It enabled to account for a combination of species and systems not present in most studies at farm level, which largely focused on singles species. It also enabled to account for regional specificities of production systems (e.g. feed resources and farming practices) not accounted for in global studies. To move forward, it would be interesting to downscaling our analysis to a lower level, such as the small agricultural region, which might be more appropriate for assessing for instance local environmental impacts and biodiversity (Teillard d'Eyry, 2012).

In a nutshell:

- The current heterogeneity of livestock production areas emerged as a consequence of varied trajectories of intensification that led to marked spatial differentiation in the livestock sector
- Areas following a high intensification trajectory of livestock production were important in terms of provisioning of animal source food, but unsustainable in terms of environmental quality
- A compromise is needed between food production and environmental quality
- Areas following an extensive trajectory deserves more attention, as they are overall more sustainable. They put meaning back to livestock evolutionary ability of transforming non-human edible resources into high quality foods for human consumption and provide multifunctional bundle of social, cultural and environmental services to society.

B. APPENDIX

V. UNRAVELLING THE PHYSICAL, TECHNOLOGICAL, AND ECONOMIC FACTORS DRIVING THE INTENSIFICATION TRAJECTORIES OF LIVESTOCK SYSTEMS

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Abstract

Over the past 100 years, the French livestock sector has experienced significant intensification that has occurred in different ways across the country. Specifically, France has changed from a homogeneous state with most of the agricultural area covered by grasslands and a uniform distribution of animals, to a heterogeneous state characterised by an uneven distribution of grasslands, livestock numbers, and livestock species. Studying the dynamics of this change is fundamental to the identification of drivers that shaped the various intensification trajectories and led to these different states, as well as to the prediction of future changes. Hence, the objective of this study was to characterise the trajectories undertaken by the French livestock sector to understand the intensification process and the role of socioeconomic, land use, and production-related factors. A set of 10 indicators was employed to analyse the main changes between 1938 and 2010, using principal component analysis followed by a clustering of the 88 French departments. Between 1938 and 2010, significant increases in farm size, mechanisation, labour productivity, and the stocking rates of monogastrics enabled the French livestock sector to double its production. The most important changes involved mechanisation (with the number of tractors per hectare [ha] rising from 0.0012 to 0.0053), labour productivity (improving from 8.6 to 35.9 ha per worker), livestock production (e.g. milk production increasing from 758 to 1856 litres per ha of fodder area) and stocking rates (rising from 0.57 to 0.98 livestock units [LU] per ha). The increased heterogeneity apparent in the patterns of change throughout France's departments was captured by clustering four trajectories. Two trajectories were formed by departments that experienced strong specialisation towards livestock production, with one type mainly orientated towards high-intensive dairy, poultry, and pig landless production systems, and a second type orientated towards extensive beef grazing production systems. Another trajectory corresponded to departments that specialized in crop production with high labour productivity; mixed crop-livestock systems were still maintained at the margins of this group of departments. The fourth trajectory corresponded to the lowest livestock population and productivity levels. The increase in mechanisation during the period was important but uniform, with no significant differences between the trajectories. This typology of intensification trajectories will enable the targeting of specific areas in which the detrimental impacts of livestock intensification require mitigation and provide guidance for future livestock sector developments.

Keywords: livestock farming systems, drivers of change, intensification dynamics, land use change, long-term trajectories

Implications

Understanding the temporal trajectories of livestock systems could steer livestock systems towards sustainable development. Our approach provides information regarding the factors that have shaped the systems' current intensification patterns, which can be used to examine how policy incentives might influence these factors to achieve desirable long-term changes. The information generated in this study is relevant to decision-makers, as it focuses on the level at which agricultural issues and natural resources are managed, and on the level at which the different livestock systems are combined.

Introduction

The global livestock sector currently faces the significant challenge of increasing production in response to a rapidly growing demand while minimizing adverse environmental impacts and pressures on natural resources (Godfray et al., 2012; Gerber et al., 2014). In the past, increased food production was achieved by a drastic intensification of production systems, which is a trend that is likely to continue (Thornton, 2010). Hence, concerns regarding environmental and ethical issues have fostered the concept of sustainable production intensification (Garnett and Godfray, 2012).

In Europe, changing animal feeding patterns, such as the shift from diets primarily based on fodders and food wastes in the early 20th century to diets rich in concentrates in recent decades, were followed by changes in land use and the conversion of grassland to cropland (Mazoyer and Roudart, 2006; Potter and Lobley, 1996). These changes, which characterised the intensification process (Lassaletta et al., 2014; Bouwman et al., 2005), also decreased the amounts of nutrients that were recycled within the livestock production system and increased the imports of protein feed concentrate. The factors underlying these changes have been identified including the economic influences (the rising demand for livestock products), technological considerations (advances in breeding and genetics, nutrition, and disease; Thornton, 2010), and changes in land use (Alexander et al., 2015). Their respective roles have likewise been qualitatively addressed, but they have not been hierarchised or simultaneously analysed to gain insight on intensification patterns. Thus, a broader, more comprehensive understanding of these patterns is needed to unravel the interplay between the driving factors, to rank their respective contributions and to explain the current configuration of the livestock sector. Understanding prior change patterns is useful in acquiring region-specific information that takes the particular regional context, history, and the inertia of current trends into account, which could foster sustainable intensification strategies.

Previous studies of agricultural dynamics provided information on the drivers of agricultural change from different perspectives including the types of farming activities, time periods, geographical locations, and levels of analysis. Mottet et al. (2006) studied changes in agricultural land use in the French Pyrenees from 1950 to 2003 and its drivers from a landscape perspective, whereas Garcia-Martinez et al. (2009) studied changes in cattle farming that occurred in the Spanish Pyrenees between 1990 and 2004. More recently, Ryschawy et al. (2013) identified pathways that enabled the survival of mixed crop-livestock systems in the French Coteaux de Gascogne region. Hazell and Wood (2007) reviewed the main drivers of change at the global, national, and local levels and listed the drivers by level, degree of importance, and rate of change. These prior reports succeeded in presenting a detailed view of the changes that occurred in a specific area, mostly at the farm level. However, no prior studies account for the interplay of the multiple factors that drive the dynamics of livestock systems or the resulting consequences on intensification on large gradients.

Intensification can be seen as a process that increases land productivity by expanding input use per unit area (Shriar, 2000), or as the set of possible combinations of labour-, capital-, and technology-related parameters that achieve a higher production per unit area. Therefore, intensification can be measured by the quantity of production per area or per animal as well as by the quantity of inputs per unit area or animal or by a quantity of input per unit product (Herzog et al., 2006; Temme and Verburg, 2011; Teillard et al., 2012). Changes in land can be classified into two types: (a) changes in land cover that alter the biophysical characteristics of the land via the expansion or contraction of a given land use type, such as the encroachment of cultivated crops into permanent grassland areas, or (b) changes in land use intensity accompanied by changes in the levels of socioeconomic inputs to the land (e.g., labour, feed resources, or capital) and/or altered outputs per unit area and time, such as increased animal stocking rates (Erb, 2012).

Prior changes in livestock production were associated with technological progress related to animal nutrition, breeding, and health (Thornton, 2010). Not only have these contributed to the intensification of the livestock sector, but also to high-yielding crop varieties and increased reliance on fertilisers, irrigation, and agro-chemicals (Hazell and Wood, 2007). Another important change was the specialisation of the livestock sector, with livestock populations growing or shrinking in certain regions (Neumann et al., 2009). The combination of improved technology and socioeconomic and land use changes were important determinants of intensification and were directly reflected by productivity levels or stocking rates. However, the exact roles of these determinants in a variety of biophysical contexts over a period that is sufficient to capture significant changes remain unclear.

The objective of this study was to determine the effects of technical, land use, and socioeconomic factors by analysing the intensification trajectories undertaken by the French livestock sector between 1938 and 2010. France is an interesting case study, because the French livestock sector strongly influences land use, occupying roughly 50% of the utilised agricultural area (UAA) in 2010 for fodder production and 14% for feed concentrate (Agreste, 2015). In terms of reared species, level of intensity, combination of production factors (land, labour, and capital) and edaphoclimatic conditions, France has one of the European Union's (EU) most diversified livestock sectors. We adapted the methods used to analyse farm dynamics and applied them to the department (a French administrative entity), which is a higher aggregation level, to gain insight into the factors that are driving the intensification process. Our analysis is based on quantitative data obtained for 88 French departments over nearly the past century, with the goal of identifying important changes in intensification and the drivers affecting the noted change.

Material and methods

Methodological approach main feature

To study changes in livestock production over time, we utilised the within-class principal component analysis (PCA) method developed by Dolédec and Chessel (1987), which was designed to analyse the spatiotemporal changes in a given system and had previously been used to analyse changes in livestock farms (Garcia-Martinez et al., 2009; Ryschawy et al., 2013). The within-class PCA method enables a distinction to be made between the effects due to structural factors and the effects of time in change trajectories. Trajectory analyses emphasise changes over a long period, rather than the analysis of a select instant in time, which could yield a simplified view of reality. Our analysis was dynamic, and included a diverse set of variables (technical, land use, and socioeconomic), which enabled us to capture important factors in the process of livestock production intensification.

Thus, French livestock systems serve as representative examples of the variety observed in Europe. A detailed description of the data compilation and the statistical analysis is provided in the following section.

Data series, sources, and indicator selection

A large French livestock database was available at the department level (Territorial Units for Statistics 3 level NUTS3) (Cavailhes et al., 1987), which provided the unique opportunity to trace changes in the departments over long periods (years 1938, 1955, 1970, and 1980). A collation of more recent data from the agricultural census allowed us to extend the series through to 1988, 2000 and 2010 (Agreste, 2015). This extensive period ranging from 1938 to 2010 made it possible to capture major changes related to farm modernisation and the European Common Agricultural Policy (CAP) that occurred after WWII (Fearne, 1997; Isoni, 2015). The initial database (Cavailhes et al. 1987) did not provide any estimates of pig or poultry production, which were mainly associated with subsistence farming from 1938 until the 1970s, reflecting the reduced importance of trade and the lack of statistics regarding the production of monogastrics. Nevertheless, we considered data on the population of monogastrics, which were available since 1938.

Data were organized into three categories of variables: land use, socioeconomic, and livestock (**Table V-1**). The land use variables characterised the relative importance of fodder and arable land in the departments and were used to rank the lands according to the area allocated to fodder production for livestock. The socioeconomic variables involved labour workforce availability, mechanisation, farm size, and dependence on purchased feed. The livestock variables included population size and the stocking rate of herbivores (cattle, sheep, goats, and horses) or monogastrics (pigs and poultry), as well as herbivore meat and milk production. Data were assembled in a table (D), composed of v continuous variables (v = 10), d departments (d = 88) and y years (y = 7), so that each data point in D refers to a specific variable v, for year y and department d (**Table V-1**). The table D was not shown in this paper because it is a long table, with 616 rows (88 departments x 7 years) and 10 columns (10 variables).

Table V-1. Correlation coefficients between intensification and services provisioning variables from French departments.

Variable name	Abbreviation	Units
Livestock variables		
Livestock Units (cattle, sheep, goat, horse, pig, poultry)[1]	LU	LU
Herbivore Livestock Units	Herb LU	LU
Monogastric Livestock Units	Mon LU	LU
Herbivore stocking rate*	Herb SR	$LU.ha^{-1}$
Monogastric stocking rate*	Mon SR	$LU.ha^{-1}$
Herbivore meat production per main fodder area (cattle, sheep, and goat meat)*	Herb Meat MFA	$kg.ha^{-1}$
Milk production per main fodder area (cow, sheep, and goat milk)*	Milk MFA	$litres.ha^{-1}$
Land-use variables		
Utilised Agricultural Area	UAA	ha
Main Fodder Area	MFA	ha
Share of utilised agricultural area in the department*	UAA:DEP	-
Share of main fodder area in utilised agricultural area *	MFA:UAA	-
Socioeconomic variables		
Number of farms	Nb farms	-
Annual Work Unit[2]	AWU	AWU
Average farm size*	FAS	ha
Labour productivity*	UAA:AWU	$ha.AWU^{-1}$
Dependence ratio (purchased feed/ final livestock output)*	Depend ratio	-
Tractor density*	Tractor dens	$Tractors.ha^{-1}$

*Variables used in the Principal Component Analysis; 1) Complying with Eurostat standard. 2) Before 1970 accounts only for male workers, but after 1980 accounts for the work performed by one person on an agricultural holding on a full-time basis.

Statistical analysis of trajectories

The statistical analysis of the department trajectories included four major steps: principal component analysis (PCA), between-class analysis, within-class analysis, and a hierarchical cluster analysis (HCA).

First, PCA was performed on all data in table D to reduce the number of variables while maintaining the largest possible variance. We used the Kaiser criterion to select four factors with eigenvalues >1, which explained 80.9% of the total variance, and resulted in the generation of a new table (DN). Second, a between-class analysis and a within-class analysis were performed on table DN. The between-class analysis enabled the identification of the variables that had undergone the greatest change between the years, removing the effects of time, whereas the within-class analysis enabled the identification of the variables that had undergone similar changes within the years, which accounted for the effects of time. Third, we analysed the results of the within-class analysis using the Kaiser criterion to select three factors that explained 73.6% of the total variance between the departments' trajectories. Fourth, a HCA based on the squared Euclidean distance and Ward's aggregation method was performed on the three factors of within-class analysis and the typology of departments was generated based on their change trajectories. An analysis of variance (ANOVA) followed by the Tukey's test was performed on HCA results to compare trajectory's means for significant statistic difference at $P < 0.05$. All statistical procedures, including the PCA, between-class analysis, within-class analysis, HCA, ANOVA, and Tukey's test, were performed using the R software package (R Core Team, 2015).

Results

General change trends

At the national level, the between-class analysis results reflected the major changes over study period. The most important changes in the livestock intensification process were observed in the socioeconomic variables, with a 4-fold increase in the indicators of mechanisation and labour productivity between 1938 and 2010 (**Table V-2**). Further, tractor density rose from 0.0012 tractors per ha in 1938 to 0.0053 in 2010, and labour productivity increased from 8.6 ha per annual work unit (AWU) in 1938 to 35.9 ha in 2010. **Table V-2** also indicates a significant reduction in the number of farms, from 2 million in 1938 to 0.5 million in 2010, which contributed to farm enlargement.

Important gains were also detected in the livestock variables. The stocking rate of monogastrics increased approximately 170%, due to the rising population of monogastrics (+130%), which was concurrent with a slight reduction in the utilised agricultural area (-15%). Conversely, the apparent increase in the herbivore stocking rate was much smaller (+50%). Milk production per unit of main fodder area (MFA) increased by a factor of 2.4, from 758 kg per ha to 1,856 kg per ha over the period studied. Herbivore meat production per MFA roughly doubled, from 60 kg ha-1 in 1938 to 118 kg ha-1 in 2010, reaching peak production in 2000 (124 kg.ha-1) and returning to the 1980 level (118 kg.ha-1) by

2010. Increases in milk and meat production were mainly due to improved livestock performance in terms of meat and milk yield per animal, which was aided by a smaller but intensified MFA. The livestock sector relied more on external inputs in 2010 than in 1938, with the dependence ratio increasing by 78% over the period. This was partly due to a higher share of monogastrics in the total livestock population, rising from 18% to 28%, as monogastrics relied more on purchased feed concentrate than herbivores.

Table V-2. National changes in livestock production, land use, and socioeconomic variables in France's 88 departments.

	1938	1955	1970	1980	1988	2000	2010	1938-2010
Livestock Units (LU)	17 916	18 636	22 031	24 210	28 951	28 112	26 368	47%
Herbivore LU	14 624	15 211	17 381	18 917	22 503	20 090	18 787	28%
Herbivore Stocking Rate	0.47	0.51	0.54	0.61	0.79	0.73	0.70	50%
Monogastric LU	3 292	3 426	4 650	5 293	6 448	8 022	7 582	130%
Monogastric Stocking Rate	0.10	0.11	0.14	0.17	0.23	0.29	0.28	170%
Herb meat product: MFA	60	75	93	118	99	124	118	95%
Milk production: MFA	758	933	1127	1473	1576	1807	1856	145%
Utilised Agric. Area (UAA)	31 359	29 978	32 114	30 995	28 471	27 700	26 795	-15%
Main Fodder Area (MFA)	18 806	19 102	17 703	16 433	14 503	12 778	12 380	-34%
UAA: Department Area	0.58	0.55	0.59	0.57	0.52	0.51	0.49	-15%
MFA:UAA	0.60	0.64	0.55	0.53	0.51	0.46	0.46	-23%
Number of farms	2 067	2 246	1 578	1 255	1 012	660	487	-76%
Annual Work Unit (AWU)	3 637	3 381	2 290	1 863	1 439	953	747	-79%
Average farm size	15.2	13.3	20.4	24.7	28.1	42.0	55.0	263%
Labour productivity	8.6	8.9	14.0	16.6	19.8	29.1	35.9	316%
Dependence ratio	0.15	0.18	0.21	0.28	0.25	0.26	0.28	78%
Tractor density	0.0012	0.0020	0.0052	0.0059	0.0053	0.0052	0.0053	337%

The results at the department level differed. In 1938, there was a close and local linkage between livestock and land use across the country, as 80% of the departments had allocated at least 50% of the UAA to fodder production (**Figure V-1**), and livestock was present in all departments (**Figure V-2**). In 2010, a more specialised pattern of land use was observed, with formerly dominant fodder land being cleared for cropland. Only 50% of the departments had allocated at least 50% of the UAA to fodder production (**Figure V-1**), and the livestock population was concentrated in a limited number of departments located in the Western and Central areas of France (**Figure V-2**). Combined, the two areas hosted approximately 80% of the national livestock population in 2010.

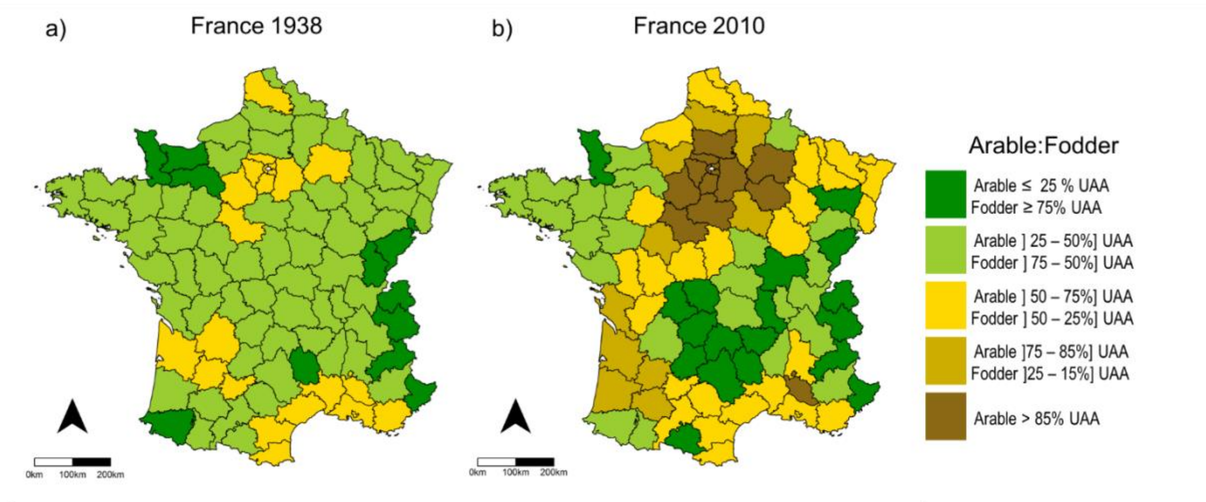

Figure V-1. The evolution of land use in France at the department level from 1938 (a) to 2010 (b) in terms of arable crop and main fodder area in utilised agricultural area (UAA).

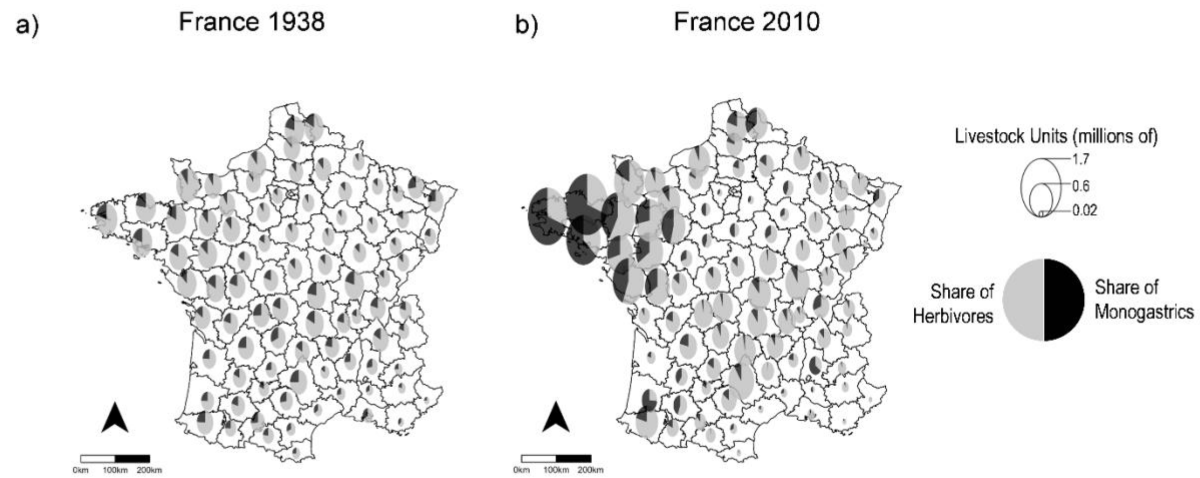

Figure V-2. The changes in the livestock population of herbivores (cattle, sheep, goat, horse) and monogastrics (pig, poultry) and in the species composition over time in France at the department level from 1938 (a) to 2010 (b).

Trajectories of change at the Department level

The within-class analysis conducted on data from the entire set of departments resulted in the identification of three factors with an eigenvalue >1. These factors explained 30.6%, 22.1% and 20.1% of the total variance, respectively. Factor 1 was primarily related to the combination of herbivore milk and meat production and the stocking rates of herbivores and monogastrics, and corresponded to a gradient in livestock production intensification, ranging from departments with high productivity and stocking rates to departments with a limited number of livestock. Factor 2 was generally positively related to the share of MFA and herbivore stocking rate, and negatively related to the average farm size and labour productivity, ranging from departments that emphasised grazing to departments that specialised in cropland. Factor 3 was mainly positively related to the dependence ratio and the monogastric stocking rate and negatively related to the share of MFA and herbivore stocking rate, ranging from a greater dependence on purchased feed and an increased monogastric population to a reduced dependence on purchased feed and a larger number of herbivores. The HCA carried out on these 3 factors identified four trajectories within the departments. **Figure V-3** shows the projection of these four trajectories on the first and second components of the within-class analysis. **Figure V-4** shows the projection of the trajectories on a NUTS3 level map of France. **Figure V-5** shows the quantitative changes in the selected variables for each trajectory. A table listing the quantitative changes in all variables is available in the Supplementary Table S1.

The type 1 trajectory (T1; n = 16) included the departments located in Western France that were characterised by the most intensive livestock production systems. The type 1 trajectory also exhibited the most significant increases in livestock numbers and productivity indicators, with the inherent animal populations and productivity more than doubling. Further, the most marked characteristic of this trajectory was the size of its population of monogastrics, which increased 6-fold from an average of 58,000 livestock units (LU) in 1938 to 344,000 LU in 2010. In 2010, T1 hosted 72% of the monogastric population in the country. The 7-fold increase in the monogastric stocking rate, from 0.12 LU.ha^{-1} in 1938 to 0.84 LU.ha^{-1} in 2010, was higher than the population growth due to the concurrent 15% decrease in the UAA. Important gains in productivity were achieved, with milk production per ha of MFA rising from 990 litres in 1939 to 3,773 litres in 2010. This productivity gain was nevertheless realised at the expense of the dependence ratio, which almost tripled and was the highest among all trajectories in 2010. The higher dependence ratio reflected a characteristic of very intensive systems such as in landless monogastric or dairy production that relied heavily on purchased feed. As well, a 9-fold increase in mechanisation was necessary to sustain the livestock demand for feed (maize cropping and haymaking). Such gains in mechanisation contributed to the 4-fold gain in labour productivity, which increased from 8.8 ha per AWU in 1938 to 35.6 ha.AWU-1 in 2010.

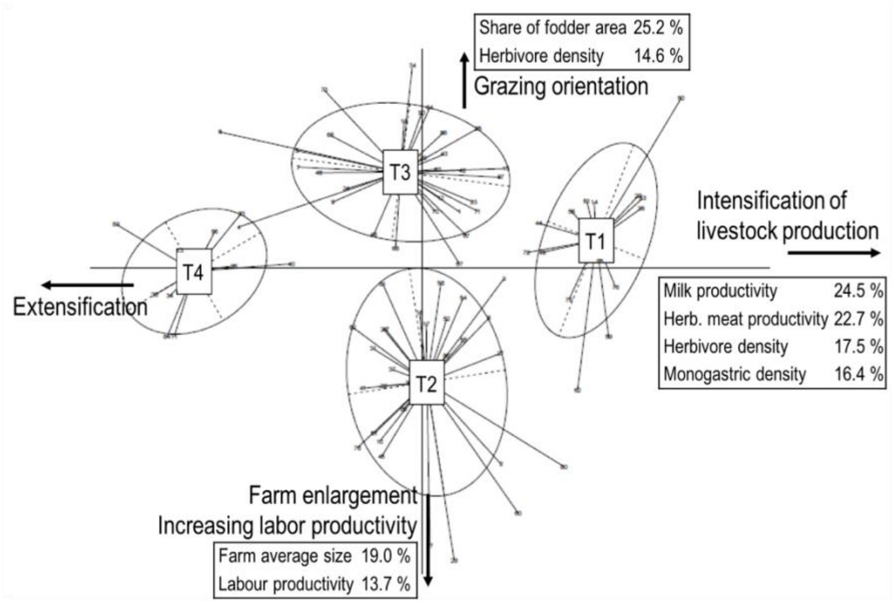

Figure V-3. Projection of the four types of trajectories on the first and second components of the within-analysis after the hierarchical cluster analysis. Each trajectory is formed by individual departments with similar intensification trends. The main variables and their contribution to the component variance is presented for each trajectory. Component 1 explained 30.6% of the variance between the departments. Component 2 explained 22.1% of the variance.

The type 2 trajectory (T2; n = 30) included departments located in the core and surrounding Parisian Basin that were characterised by crop or mixed crop-livestock systems. The T2 departments were primarily distinguished by the highest total increase in the average farm size and in labour productivity. Farm enlargement was followed by arable crop expansion over the MFA. There was a small decline in livestock units (-4%) over the period between 1938 and 2010, with a slight decrease in herbivores (-6%) and a concurrent small increase in monogastrics (+8%). In 2010, herbivore meat and milk production equalled 126 kg and 1,736 kg per ha of fodder area, respectively, which corresponded to increases of 117% and 138% over the period, respectively.

The type 3 trajectory (T3; n = 32) included departments located in the East and central mountainous areas with an emphasis on grazing systems (Figure 6). Although trajectories T1, T2, and T4 lost MFA to crop land, T3 was the only trajectory that displayed a slight increase in MFA in the UAA (+5%). On average, MFA accounted for 73% of the UAA in 2010. The herbivore population underwent a 50% increase between 1938 and 2010, whereas the population of monogastrics declined by 35%. The emphasis on grazing relied predominantly on local fodder resources and was associated with a moderate increase in the 'dependence ratio' of 64% during the period compared to its 300% increase in T1.

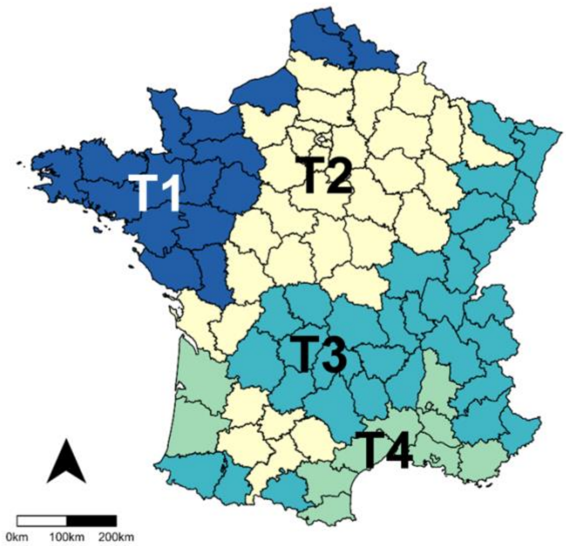

Figure V-4. Location of the four intensification trajectories in France at the department level. T1, 2, 3, and 4 correspond to 'High intensification of livestock production', 'Crop orientation and intermediate intensification of livestock', 'Grazing orientation of livestock production', and 'Non-livestock dominated' departments, respectively.

The type 4 trajectory (T4; n = 10) included departments located in the Mediterranean and South-West regions, which experienced the highest UAA (-28%) loss rate, dropping from 226,000 ha in 1938 to 162,000 ha in 2010. In 2010, UAA accounted for 26% of the department areas, which was far below the country average of 49%, indicating the minor importance of agriculture in this trajectory. A 48% reduction in MFA, from 91,800 to 47,600 ha, was observed along with a halving of the herbivore population from 67,000 in 1938 to 34,100 LU in 2010. As well, the T4 trajectory had no significant emphasis on livestock production compared to the other trajectories. Livestock productivity was low and tended to decline between 1938 and 2010 with meat and milk production per ha of MFA falling from 39 kg to 32 kg and from 616 litres to 444 litres, respectively.

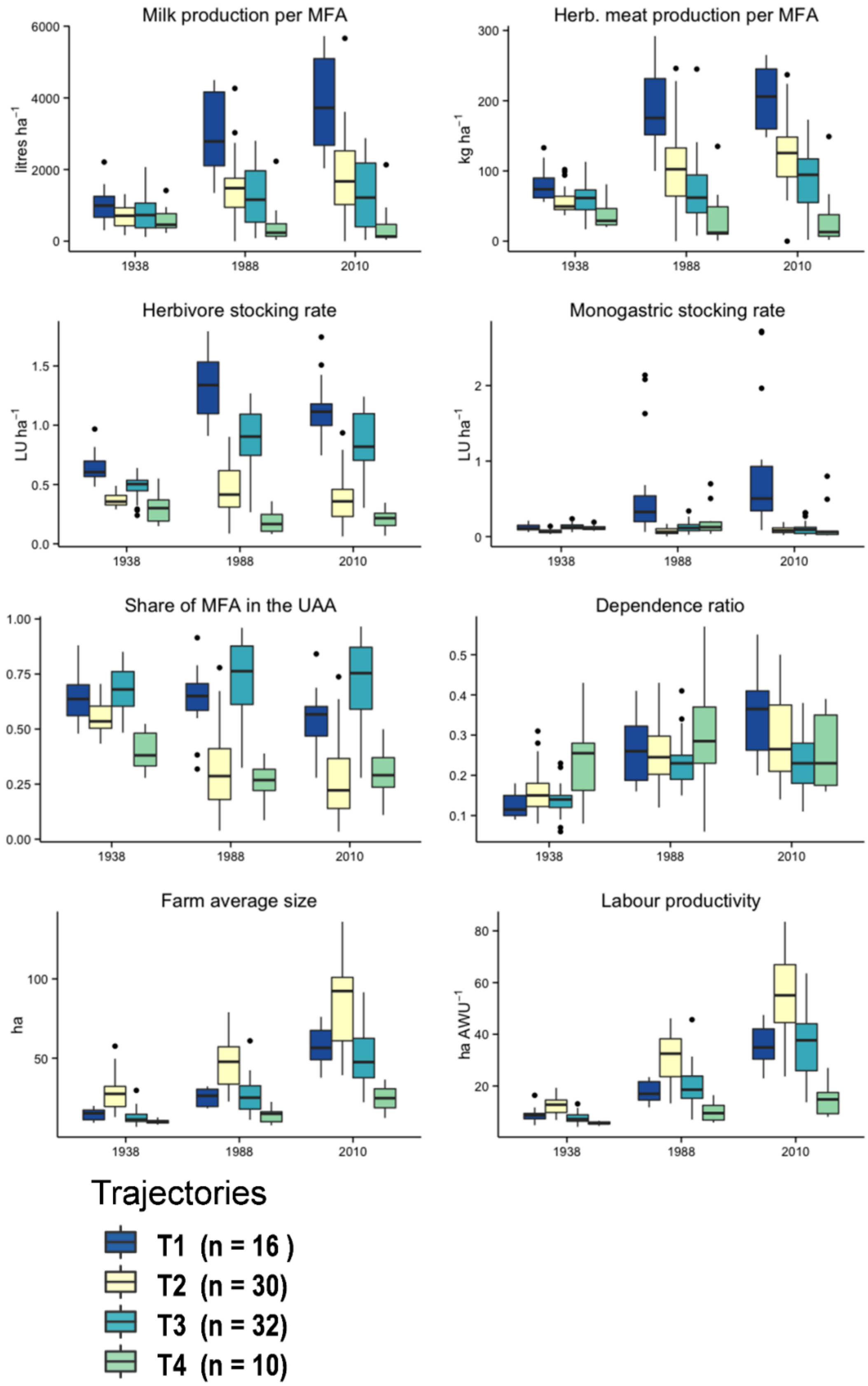

Figure V-5. Trends of change observed in the French departments per type of trajectory. T1, 2, 3, and 4 correspond to 'High intensification of livestock production', 'Crop orientation and intermediate intensification of livestock', 'Grazing orientation of livestock production', and 'Non-livestock dominated' departments, respectively.

Discussion

The interplay of biophysical and socioeconomic drivers in the intensification patterns

Our analysis revealed that the intensification of the French livestock sector was spatially differentiated and based on four different trajectories. The type 1 and 3 trajectories were characterised by a gradient in the intensification and specialisation ranging from intensive monogastric/herbivore stocking rates to extensive herbivore livestock production. The type 2 trajectory represented a specialisation towards crop production while maintaining a limited number of herbivores at an intermediate meat and milk production level. The type 4 trajectory exhibited the lowest livestock population and productivity levels.

Our work confirms prior studies from Peyraud et al. (2014), which indicated that biophysical factors emerged as the predominant drivers of intensification patterns in particular parts of France. We found that regions with marginal or mountainous land offered greater opportunities for developing grasslands and herbivore production (T3) compared to food crops, which were not profitable on this type of land. The regions containing better quality soils fostered the development of food crops (T2) as well as livestock diets based on arable crops (cereals and oil-protein crops). The abundance of crop products also enabled the development of monogastrics (T1). The apparent trend was in accord with patterns observed in Austria between 1950 and 1955 (Krausmann et al., 2003), with a concentration of cropland areas in the fertile lowlands and the predominance of livestock production in the lower alpine regions. Peyraud et al. (2014) also highlighted the interplay between agronomic potential and socioeconomic factors such as farm size, and reported the significant development of the livestock sector in Western France (Brittany), followed by a specialisation, which corresponds to our Type 1 trajectory, and a decrease in permanent grasslands giving way to annual crop production in the Northern France (Paris basin), which corresponds to our Type 2 trajectory.

The evolution of socioeconomic factors involved changes in the availability of labour in rural areas that occurred with the advent of mechanisation and the replacement of labour force by tractors, which played a critical role in determining farming orientation (crop versus livestock). The development of intensive livestock farming in Western France (Brittany) that began in the mid-twentieth century was made possible by a historically high rural population density, which provided the manpower for animal farming (Gambino, 2014). Another fundamental aspect includes the structural changes related to the labour opportunity costs due to competition with other sectors for labour force, which ultimately resulted in land abandonment (Garcia-Martinez et al., 2009).

Our findings likewise support the trends reported by Veysset et al. (2005) regarding farmer’s land cover choices in response to the economic and political environment. The EU CAP allowances and global markets favoured the development of arable crops, which ultimately encroached on the grasslands in departments with appropriate pedoclimate conditions (MacDonald et al., 2000). In our study, similar trends were observed in trajectory T2 in which cropland replaced more than half of the initial area allocated to fodder. In the department trajectories located in marginal land, such as T3, the topography was mainly characterised by mountainous areas that were unsuitable for the development of arable crops (**Figure V-6**). Hence, farmers maintained extensive grassland systems due to the lack of more rewarding opportunities. Xiao et al. (2015) also observed a reduction in grassland areas in France as a result of grassland-to-cropland conversion and the competition for land between agriculture and other activities, although the study covered a more abbreviated timeframe (1992–2010).

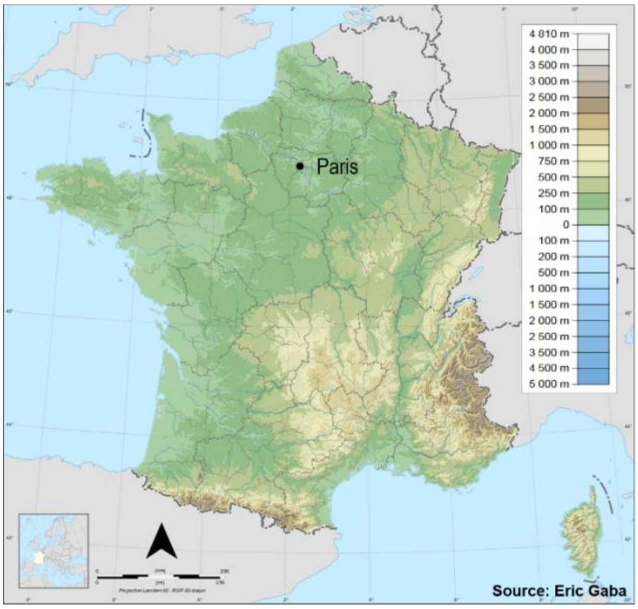

Figure V-6. Topographical map of France with an altitude gradient from light green for the plains to brown for the mountainous areas.

Interactions between department and country level

The way each department's trajectory influenced the national trends depended on the type of variable considered (whether related to livestock, socioeconomic aspects or land use). These variables differed in magnitude and even changed in opposite directions from department to country level. The overall increase in livestock-related variables at the national level emerged as a result of heterogeneous patterns of change at the department level. Most of the increases in livestock production and productivity at the national level arose in departments that followed type T1 and T3 trajectories, and in which 80% of the livestock population in the country was concentrated in 2010. Socioeconomic variables exhibited the highest quantitative growth during the study period and the directions of change were similar at both the national and department levels. Land use variables also displayed a similar direction of change, with the exception of the share of MFA. The national declining trend on the share of MFA concealed various levels of decline among trajectories of departments and even the increase apparent in the T3 trajectory.

Hierarchisation of factors

French livestock production doubled between 1938 and 2010 due to important gains in farm size, mechanisation, labour productivity and the development of the monogastrics population; however, the contributing factors differed at the national and department levels.

At the national level, important gains were achieved due to socioeconomic factors (farm size, mechanisation, and labour productivity) across the country. The apparent increases in farm size and labour productivity were in accord with prior reports by Garcia-Martinez et al. (2009) of the most important changes in the Spanish Pyrenees. The increased production was also dependent on escalating feed imports; thus, the land requirements for feed production were externalised (Chatzimpiros and Barles, 2010). This was in accord with the trends observed in the livestock sector in Spain between 1900 and 2008 (Soto et al., 2016). Drivers, such as increased per capita income (Hazell & Wood 2007), raised the associated labour costs and forced farmers to become more competitive. Thus, larger farms prevailed over small farms, which lead some farmers to abandon agriculture as a means of financial support. The trend in farm enlargement and increased labour productivity was observed in all trajectories, reflecting the substitution of labour by farm machinery, a development that was also noted by Rosset and Altieri (1997) in North America. Our study might have overlooked important economic or policy drivers related to either markets or the political environment (e.g. farm structure, financial conditions, fertiliser-to-crop price ratio and policy support measures), which are also very important in the intensification and specialisation process (Veysset et al., 2005; Zhang et al., 2015; Roguet et al., 2015). An improved economic data set would be necessary to develop a predictive model to gain insight into the drivers of intensification and to determine their relative importance to global agriculture as proposed by Kastner et al. (2012).

At the department level, the spatial differentiation of intensification trajectories was driven by the initial livestock population and the suitability of the land to the growth of arable crops based on topographic conditions. Previous studies also identified the importance of the initial production emphasis of farms (Mottet et al. 2006; Garcia-Martinez et al. 2009). Several land use change studies suggest the importance of land suitability (e.g. Nisar et al., 2000; IIASA/FAO, 2012; Van Zanten et al., 2016), which is an important indicator that measures the extent to which climatic, soil, and topographic conditions determine whether and how land is used for agriculture. Future research on intensification trajectories should take into account land suitability for agriculture as it might continue to change due to changing climate (Zabel et al., 2014).

Added-value and limitations of the proposed methodology

In this study, the choice of the department level and the use of an extended period of time spanning 72 years enabled a dynamic view of the intensification process and patterns of change within the livestock sector in France. Nonetheless, a finer-level analysis might reveal additional heterogeneity within the department level (Teillard et al. 2012). There is clearly a trade-off between assessing the process of intensification at a more aggregated level or at a finer resolution. On one hand, opting for the department level offered the advantage of a significant body of available data, and enabled a macro analysis covering a very large mixture of biophysical conditions. Conversely, a farm level analysis could provide a deeper understanding of the intensification process (Chantre and Cardona, 2014), although the area would be limited, the process would be more time and resource-consuming, the costs would be higher (time and money), and the accuracy would be both questionable and limited, as indicated by retrospective interviews conducted by Ryschawy et al. (2013).

The statistical method we adopted provided additional insight into the dynamics of intensification and the interplay of factors leading to the current specialisation patterns apparent in the French livestock sector. This was clearly a methodological advance compared to prior studies, as it could capture the main changes in livestock production while providing a dynamic view and a long-term perspective over a period in which the socioeconomic context drastically changed. This knowledge and vision is essential to managing livestock farming systems, whether to maintain desirable aspects of intensification or to mitigate potentially negative impacts (Darnhofer et al., 2010).

This typology could also be used to support decision-making at the regional level as it provides a spatially-differentiated assessment of intensification and highlights the technical, land use and socioeconomic variables that occur during the intensification of livestock production. This typology would likewise be valuable for studying the impacts of CAP reforms on livestock concentration and species balance (herbivores: monogastrics) and on the land use ratio (crop: grassland), as reported by Veysset et al. (2005).

From a policy-making perspective, this typology could shed light on the transition of livestock farming systems. Based on quantitative data of changes that occurred over the past 70 years, the different trajectories revealed that intensification was a spatially differentiated phenomenon, suggesting that transitions will not occur in a homogeneous fashion. Further, our typology could serve as a tool for choosing differing regions in terms of livestock intensification (Beudou et al. 2017). Finally, the different trajectories suggest the need for several strategies tailored to different contexts in the agroecological transition of livestock production.

Acknowledgements

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Supplementary Table S1 *Trends of change in the French departments per type of trajectory*

	Year	T1 (n = 16)	T2 (n = 30)	T3 (n = 32)	T4 (n = 10)
Livestock Units (LU)	1938	366 760^{a}	182 881^{b}	175 961^{b}	93 093^{c}
	1988	863 379^{a}	207 605^{b}	253 319^{b}	80 304^{b}
	2010	810 093^{a}	176 085^{b}	232 977^{b}	66 909^{b}
Herbivore LU	1938	308 890^{a}	153 472^{b}	137 716^{b}	67 048^{c}
	1988	603 153^{a}	178 256^{b}	222 857^{b}	37 363^{c}
	2010	466 198^{a}	144 221^{b}	208 115^{b}	34 104^{c}
Monogastric LU	1938	57 870^{a}	29 409^{b}	38 244^{b}	26 045^{b}
	1988	260 226^{a}	29 349^{b}	30 462^{b}	42 941^{b}
	2010	343 894^{a}	31 864^{b}	24 862^{b}	32 806^{b}
Herbivore Stocking Rate	1938	0.64^{a}	0.37^{c}	0.48^{b}	0.30^{c}
	1988	1.34^{a}	0.46^{c}	0.89^{b}	0.18^{d}
	2010	1.13^{a}	0.39^{c}	0.85^{b}	0.21^{c}
Monogastric Stocking Rate	1938	0.12^{a}	0.07^{b}	0.13^{a}	0.12^{a}
	1988	0.59^{a}	0.07^{b}	0.13^{b}	0.21^{b}
	2010	0.84^{a}	0.08^{b}	0.10^{b}	0.16^{b}
Herb meat production:MFA	1938	81^{a}	56^{bc}	61^{b}	39^{c}
	1988	184^{a}	107^{b}	70^{c}	33^{c}
	2010	209^{a}	131^{b}	88^{c}	32^{d}
Milk production:MFA	1938	990^{a}	686^{a}	754^{a}	616^{a}
	1988	3 004^{a}	1 486^{b}	1 284^{bc}	487^{c}
	2010	3 773^{a}	1 839 ^{b}	1 353^{bc}	444^{c}
Utilised Agricult. Area (UAA)	1938	484 681^{a}	411 877^{a}	280 709^{b}	226 475^{b}
	1988	449 784^{a}	392 552^{a}	238 250^{b}	187 343^{b}
	2010	413 104^{a}	376 498^{a}	226 967^{b}	162 780^{b}
Main Fodder Area (MFA)	1938	315 557^{a}	228 991^{b}	186 533^{c}	91 785^{d}
	1988	287 448^{a}	128 390^{bc}	177 513^{b}	49 997^{c}
	2010	226 262^{a}	101 621^{b}	166 778^{a}	47 583^{b}
UAA:Department Area	1938	0.76^{a}	0.65^{b}	0.49^{c}	0.36^{d}
	1988	0.71^{a}	0.61^{b}	0.41^{c}	0.30^{d}
	2010	0.65^{a}	0.59^{a}	0.39^{b}	0.26^{c}
MFA:UAA	1938	0.65^{a}	0.56^{b}	0.68^{a}	0.40^{c}
	1988	0.64^{a}	0.33^{b}	0.73^{a}	0.26^{b}
	2010	0.55^{b}	0.27^{c}	0.73^{a}	0.30^{c}
Number of farms	1938	34 841^{a}	17 551^{b}	23 659^{b}	22 559^{b}
	1988	18 304^{a}	9 345^{c}	9 434^{c}	13 654^{b}
	2010	7 440^{a}	4 975^{b}	4 780^{b}	6 591^{ab}
Annual Working Unit (AWU)	1938	59 288^{a}	35 150^{b}	38 450^{b}	40 350^{b}
	1988	26 531^{a}	13 927^{c}	12 564^{c}	19 472^{b}
	2010	12 219^{a}	7 533^{b}	6 516 ^{b}	11 734^{a}
Average Farm Size	1938	15^{b}	27^{a}	13^{b}	10^{b}
	1988	26^{bc}	46^{a}	26^{b}	14^{c}
	2010	57^{b}	85^{a}	50^{b}	25^{c}
Labour productivity	1938	8.8^{b}	12.4^{a}	7.7^{bc}	5.6^{c}
	1988	17.7^{bc}	30.8^{a}	19.8^{b}	9.9^{c}
	2010	35.6^{bc}	55.6^{a}	36.9^{b}	15.1^{c}
Dependence ratio	1938	0.13^{b}	0.16^{b}	0.14^{b}	0.24^{a}
	1988	0.26^{a}	0.26^{a}	0.23^{a}	0.30^{a}
	2010	0.35^{a}	0.29^{ab}	0.23^{b}	0.26^{ab}
Tractors density	1938	0.0006^{b}	0.0014^{b}	0.0007^{b}	0.0031^{a}
	1988	0.0056^{a}	0.0042^{b}	0.0056^{a}	0.0068^{a}
	2010	0.0057^{a}	0.0039^{b}	0.0058^{a}	0.0069^{a}

See Table V 1 in the main manuscript text for variables' units. Means followed by same letter within a row do not significantly differ by Tukey's test ($P<0.05$). Indicators are expressed as the mean of all departments belonging to each type of trajectory.

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VI. EXPLORING SYNERGIES AND TRADE-OFFS AMONG PERFORMANCE AND ENVIRONMENTAL IMPACTS INDICATORS IN LIVESTOCK AREAS

Introduction

Livestock is a major driver in the use of land and resources, and provides means of income and nutrition in both developed and developing countries. A diversity of farming systems exists due to a combination of different levels of intensification, diverse agroecological zones and production objectives, which ultimately influences the efficiency in the use of land and resources (Herrero *et al.*, 2013; Herrero *et al.*, 2015). The intensification of agriculture from the second half of the 20th century, with increased output of crops and animal source foods per unit area and time, concurred with nutrient disconnection between arable lands and livestock. This was defined by a separation of crop cultivated plains from mountain and forest areas used for grazing (Lambin *et al.*, 2001). Livestock specialisation relied on high-yielding technology packages based on improved nutrition, animal genetics and health/disease control (Gerber et al. 2015). Feeding rations characterised by rich energy-protein feeds, made systems increasingly dependent on globally sourced protein with livestock leading the global N trade (Lassaletta *et al*., 2014). Although intensification contributed to increased food production at lower prices, it raised concerns because of detrimental environmental impacts, in particular climate change, deforestation, soil degradation and alterations of global nitrogen and phosphorus cycles (Evenson and Gollin, 2003; Bouwman *et al.*, 2009). There is a consensus over the need to meet future demand of livestock products at lower environmental impact (Godfray *et al.*, 2012). This emphasises managing limited renewable and non-renewable resources to deliver a sufficient amount of plant-animal products without compromising the long-term production capacity of agro-ecosystems (Dumont *et al.*, 2014).

Many sustainability assessment of livestock systems put emphasis on the efficiency with which resources are transformed into marketable products. Herrero *et al.* (2015) described that assessing efficiency is essential, as from a productivity or environmental impacts perspective, low efficiency is often correlated with high emissions, and conversely. Although this statement is common sense in a great part of literature, the question of efficiency is actually multifaceted. Ross *et al.* (2017) reported that environmental efficiency of dairy systems depended on the functional unit to which impacts were referenced, with a system showing highest efficiency when emissions were referred to unit product, and lowest efficiency when referred to on-farm land. This highlights the need of accounting for impacts attributed to both unit produce (e.g. kg of fat-and-protein-corrected milk) and to unit of land area (e.g. farmed hectare). In addition to impacts to the environment, studies on agro-ecological farming suggested benefits of re-connecting crop and livestock systems, with better recycling of natural resources and reduced dependence to external inputs (Dumont *et al.*, 2013). Regarding the dependence on external inputs, Soteriades *et al.* (2016) assessed the eco-efficiency of dairy farms and found a negative relationship between intensification and self-sufficiency, and that although increasing milk yield per cow improved environmental performance at the cow-level, this did not hold at the farm level. These findings highlight the need of a multi-criteria approach for assessing livestock sustainability, with metrics for measuring plant and animal efficiencies, environmental impacts, self-sufficiency, as well as an account for more aggregated levels of production.

Many studies used efficiency indicators to assess the multiple components of agro-ecosystems, from inputs to soil to plant output, or plant to animal conversion, as well as aspects related to levels of analysis, ranging from animal level to more aggregated levels as regional and global. Zhang's *et al*. (2015) proposed targets to tackle triple-challenge (food security, environmental degradation and climate change) were unarguably valuable to determine where improvement is being achieved and where stronger local efforts are needed, but it lacked considerations about livestock, that together with crop systems compose the key to achieve the Sustainable Development Goals (SDSN, 2015).

Most of prior efforts to improve efficiency were achieved through animal-centred approaches, with attention mainly focused on animal performance and linked to gains in feed conversion efficiency (Iribarren et al., 2011; Zehetmeier et al., 2012; Shortall and Barnes, 2013; Mu et al., 2017). Many studies lacked necessary attention to how gains in efficiency were affecting the surrounding environment, the watershed or region for instance. Several recent studies demonstrated the need to consider efficiency beyond the animal level in order to account for the complementarity between improving yields at animal and crop levels, as well as to trade-offs of changing scales/levels (Mottet et al. 2017; Godinot et al. 2014; cite also Billen Lassaleta here). Godinot et al. (2014) developed the 'system nitrogen efficiency' (SyNE) to improve estimation of N efficiency at farm level and found for a given land productivity level (kg N output.ha^{-1}), gains in SyNE reduced potential N losses, whereas changing productivity levels, in cases of intensification would result in higher losses, and in cases of extensification would reduce losses. At regional level, Le Noë *et al.* (2017) studied nitrogen, phosphorus and carbon flows of agro-food systems, evaluated environmental and agronomic performance, and highlighted the role of specialisation and intensification on losses in cropland and grasslands. The authors developed a sophisticated method for accounting for every flow between land-based and human compartments. Regarding the livestock compartment - that in many studies are considered as the main driver of land use – it was given marginal position and used for closing/balancing flows. It thus failed to account for the large heterogeneity of livestock species reared with varied practices in relation to land and resources. At global level, Billen *et al.* (2014) had already used similar framework, and ranked the three primary drivers influencing the performance of agro-food systems, which are: the crop response (yield) to fertilizers, and feed conversion rate of livestock farming systems. This emphasises the need of a framework that gives sufficient characterisation of livestock as of crops and fodder production, that yields a multi-criteria set of indicators, and provide reliable/complete assessment of the complexity of livestock in the agro-ecosystems.

Thus, an assessment of livestock production systems and accounting to their components complexity (species composition, feed diversity and practices) and interactions (performance and impacts), would be of valuable knowledge to identify overall potential for livestock systems improvement and the room for manoeuvre to increase performance and decrease impact to the environment.

The objective of this study was to identify the spatial differentiation of trade-offs and synergies among performance and environmental impact indicators across livestock dominated areas in France. We used the material flows analyses to quantify the nitrogen flows of livestock systems, and applied it to 48 departments (a French administrative entity). We derived indicators of performance and impact from the inventory of flows to identify types of interactions, classed as synergies or trade-offs. Our analysis relies on a comprehensive account of the heterogeneity of livestock systems and the set of indicators is representative of plant and animal efficiencies, feed sourcing, and environmental impacts from a local to global perspective.

Material and methods

Multi-approach combination

The analysis of synergies and trade-offs among performance and environmental impact indicators across livestock dominated areas in France included four major steps:

- the conceptualization and computing of the livestock metabolism and selection of indicators;
- the analysis of interactions among indicators of performance and impact;
- the spatial decomposition and mapping of interactions;
- the classification of spatial patterns of interactions followed by clustering.

The livestock metabolism

The methodological approach adopted in this is study is mainly inspired from the GRAFS approach (Generic Representation of Agro-Food Systems) as proposed by Billen et al. (2014). The GRAFS approach describes the agro-food system of a given area and considers flows of nutrients between four main compartments: cropland, grassland, livestock biomass, the local population. It also accounts for potential losses to the environment associated to flows exchanges among compartments (Le Noë *et al.*, 2017). We adapted the original GRAFS calculations and updated it to give livestock a more accountable position in the use of land-based resources. This puts livestock as a direct driver of flows, through feed sourcing from the crop and fodder compartments, rather than simply a compartment of balancing out other flows as in the initial GRAFS approach.

Another important innovation consists of characterising livestock heterogeneity at the finest level available, by compiling data that reflect the diversity of existing feeding systems, we distinguished 17 different types of feeding regimes in dairy production, 9 types in beef production, 4 types in goat and sheep production, as well as to 5 poultry species and growing pigs and breeding animals. On the top of that, our method accounts for local availability of feed resources, as all the diversity of feeding regimes are calculated relative to a specific regional context. The system boundary defined in this study is the French administrative entity called ‘department’, equivalent to the NUTS3 level of the classification of the economic territory of the EU.

Indicators derived from the inventory of N flows

From the inventory of N flows we derived metrics to describe livestock systems at department level in terms of their performance and impacts. We built a multi-criteria set of indicators that cover different dimensions of livestock system sustainability. Six indicators measured efficiency of fodder and livestock production, department feed self-sufficiency and animal source food supply, as well as impact measures from local and global perspectives. Indicators related to environmental objectives with a regional target were area-based; whereas indicators with a global focus, such as nitrogen emissions were product-based (Halberg et al., 2005). A description of each indicator is provided below.

- *Fodder Nitrogen Use Efficiency (NUE)*

The NUE indicator reports the efficiency of fodder to transform N inputs to the soil into N harvested end products to livestock (Connant et al. 2013). It constitutes an important account of resources use efficiency as livestock overall sustainability largely depends on the efficiency of which feed is produced.

$$Fodder\ NUE = \frac{NHarv}{\sum Inputs} \tag{24}$$

where $NHarv$ was the N harvested of fodder production, and $\sum Inputs$ was the sum of all N inputs (fertilizers, fixation, organic application, deposition) used in the fodder cultivation.

- *Livestock Nitrogen Feed Conversion Ratio (FCR)*

The N FCR is a measure of the plant to animal protein conversion efficiency, which indirectly determines the remaining amount of excreted N that can be recycled back to agricultural land in the form of organic fertilizer or end up in water streams and cause environmental pollution (Billen et al. 2014).

$$N\ FCR = \frac{\sum ASF}{\sum FeedCons} \tag{25}$$

where $\sum ASF$ is the total N recovered in livestock products of all species, and $\sum FeedCons$ the sum of N in feed resources consumed.

- *Nitrogen Self-Sufficiency (NSS)*

The NSS is an indicator that measures the capacity of regions to provide local feed resources in order to meet local livestock feed demand (EFESE[7]).It was calculated as follows:

$$NSS = \frac{\sum LocalFeed}{\sum FeedCons} \tag{26}$$

where $\sum LocalFeed$ was the sum of local feed resources fed to livestock, and $\sum FeedCons$ the sum of total N in feed resources consumed by all livestock species.

- *Animal Source Food (ASF)*

The ASF indicator comprises the sum of livestock production (ton) including: beef and dairy, sheep and goat meat and milk, pork, poultry meat and eggs. It was computed in terms of nitrogen and represents the local ability a region has to provide human-edible animal protein (Speedy, 2003).

- *N surplus (NSU)*

The estimate of the potential N surplus was calculated as the difference between N inputs and N outputs on fodder and cropland. We calculated the N surplus (kg) reported per hectare of crop area as a measure of N pressure, thus representing the potential local impact caused by livestock (Poisvert et al., 2017). The details of N surplus calculation is available in equation 19.

[7] L'évaluation française des écosystèmes et des services écosystémiques (EFESE, 2017)

- *N Excretion Emissions (NEE)*

N Excretion Emission included emissions related to the N volatilization of NH_3 and the emission of N_2O derived from livestock excreta during grazing (with urine and dung deposition on pastures). Emissions also included volatilization during housing and in manure storage facilities, and application of N organic fertilizer on crops and fodder (Webb et al., 2005; Lesschen et al., 2011). We calculated the N Excretion Emissions (kg) reported per kg of ASF as a measure of potential global impact caused by livestock.

Analysing pair-wise interactions among indicators – Synergies and Trade-offs

Six indicators were computed (**Table VI-1**) for a set of 48 NUTS3 which gathered the main livestock areas and both extremes of intensification trajectories (Domingues et al. 2017). The six indicators were combined two at a time, which resulted in 15 interactions.

$$C_{n,p} = \frac{n!}{p!\,(n-p)!}$$

$$C_{6,2} = \frac{6!}{2!\,(6-2)!} = \frac{6 \times 5 \times 4 \times 3 \times 2 \times 1}{2 \times 1 \times (4 \times 3 \times 2 \times 1)} = \frac{6 \times 5}{2} = 15 \text{ interactions}$$

The Pearson correlation coefficients were calculated for all interactions (using package “Hmisc” version 3.4.1 for R - R Core Team, 2015). Eleven presented moderate or strong correlations, and four showed weak correlations (**Table VI-1**). The eleven interactions were classified according to their nature, as a synergy or a trade-off. We considered a synergistic interaction when two desirable results can be jointly increased. A desirable result can mean two things: i) improvement, if it was a performance indicator; or (ii) reduction, if it was an environmental impact indicator. Similarly, we consider a trade-off interaction when a desirable result of one indicator was increased at the cost of an undesirable result of another indicator. An undesirable result can mean two things: i) reduction, if it was a performance indicator; or ii) increase, if it was an indicator of environmental impact.

Table VI-1. Indicators classified by performance or environmental impact, and Pearson correlation coefficients, and the nature of the interactions (synergy or trade-off).

		NUE	FCR	NSS	ASF	NSU	NEE
Performance	NUE	1.00					
	FCR	-0.41	1.00				
	NSS	0.68	-0.52	1.00			
	ASF	-0.61	0.71	-0.69	1.00		
Environmental Impact	NSU	-0.89	0.65	-0.61	0.66	1.00	
	NEE	0.19	-0.93	0.38	-0.58	-0.44	1.00

NUE: Fodder Nitrogen Use Efficiency; FCR: Nitrogen Feed Conversion Ratio; NSS: Nitrogen Self-Sufficiency; ASF: Animal Source Food; NSU: Nitrogen Surplus; NEE: Nitrogen Excretion Emissions. Only interactions having moderate to high correlation coefficient are classed as synergy (green) or trade-off (orange). Weak correlation interactions are coloured in grey.

Spatial decomposition and mapping of interactions - the bagplots approach

Bag plots were used to decompose trade-offs and synergies and map their spatial variation across 48 departments. The Bagplot, is a bivariate boxplot; it was proposed by Rousseeuw et al. (1999) as tool for visualising the location, spread, correlation, skewness, and tail of data sets. It complements correlation coefficients and is a useful tool for mapping the spatial variation of trade-offs and synergies (Jolke et al, 2015).

Five steps were implemented for mapping the existing geographical patterns of performance and impact of livestock across departments. In the first step, we considered the different distribution of each indicator and transformed them for reducing skewness and data spread. The last column of **Table VI-2** contains the factors we used to transform the indicators. In the second step, we z-standardized the transformed data to a mean of zero and standard deviation of one, allowing meaningful comparisons among indicators. Third step consisted of making the bagplots with the use of package “aplpack” version 1.3.0. In the fourth step, we selected interactions that had moderate or strong correlations ($r > 0.5$; $r < -0.5$) and used the bagplot’s depth median as a reference point to separate each interaction into four quadrants (**Figure VI-1a**). The first quadrant (positive/positive space), contains departments that perform well relative to the depth median, thus labelled superior positioning. The third quadrant (negative/negative space), contains departments that had weak performance relative to the depth median, thus labelled inferior positioning. The second and fourth quadrant, positive/negative and negative/positive spaces, respectively, contain departments that perform well for one indicator and weak for the other, thus labelled intermediate positioning.

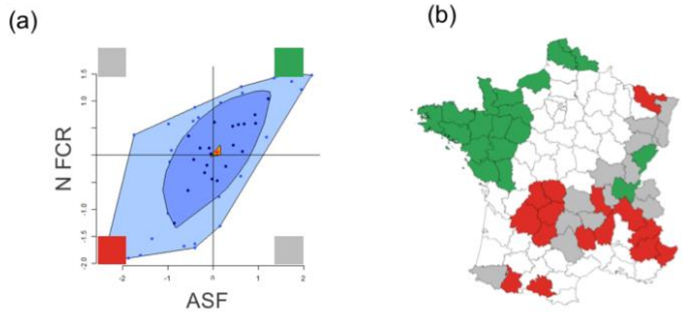

Figure VI-1. Spatial decomposition of interactions among performance and impact indicators of livestock production, applied with the use of bagplots (a) to 48 NUTS3 units in the map of France (b). Green: Superior; Red: Inferior; Grey: Intermediate ASF: Animal Source Food; FCR: Nitrogen Feed Conversion Ratio.

In the fifth step, we used the 'ggplot2' package version 1.2.3 to map each interaction, and distinguish departments according to their performance or impact (superior, inferior, etc). **Figure VI-1a-b** presents the spatial decomposition from bagplots graphs to maps of France's departments. Another two figures are presented in the Supplementary Material S2 of paper 2, with bagplots for all interactions analysed.

Table VI-2. List of indicators used in bagplots with respective units and transformation factors.

Type	Indicator	Unit	Transformation
Performance	Fodder Nitrogen Use Efficiency	%	$x^{0.9}$
	N Feed Conversion Ratio	%	$x^{0.9}$
	Animal Source Food	t of N	$x^{0.2}$
	N Self-sufficiency	%	$x^{0.9}$
Environmental Impact	N Surplus	kg N ha^{-1}	(-1) . log(1+x)
	N Excretion Emissions	kg N kg ASF^{-1}	(-1) . $x^{0.2}$

Principal component analysis and classification

After mapping the decomposition of 11 interactions we counted the frequency of events of each category (superior, inferior and intermediate) per department. Upon the table of counts we did a principal component analysis (PCA) to identify spatial patterns associated with departments' performance and impacts. A post-hoc hierarchical cluster analysis (HCA) was done on the two components with eigenvalue > 1 of the PCA to identify groups of departments with homogenous characteristics for the indicators studied.

Results

Synergies and trade-offs at national level

The patterns emerging from the 48 NUTS3 units revealed six significant synergies (**Figure VI-2**) and five trade-offs (**Figure VI-3**). Most synergies were convex (**Figure VI-2a-d-e-f**) indicating that the joint improvement of pairs of indicators was seldom achieved, and subjected to threshold effects. Three out of five trade-offs were also convex (**Figure VI-3a-b-d**) indicating strong antagonism or conflicts among indicators. Two trade-offs were concave suggesting limited antagonisms between the related pairs of indicators.

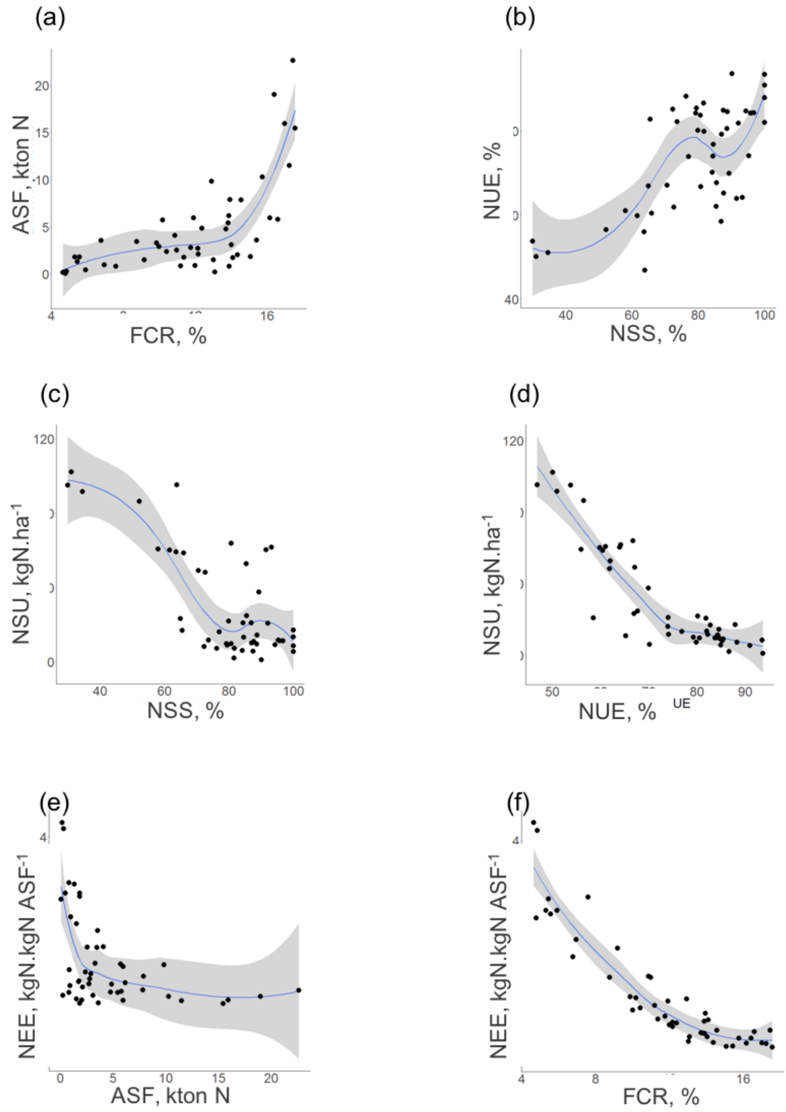

Figure VI-2. Synergies among performance (a-b) and among performance and impacts (c-f) in 48 livestock dominated NUTS3 units. ASF: Animal Source Food; FCR: Nitrogen Feed Conversion Ratio; NUE: Fodder Nitrogen Use Efficiency; NSS: Nitrogen Self-Sufficiency; NEE: N Excretion Emissions; NSU: Nitrogen Surplus.

There were two synergies among performance indicators (**Figure VI-2**a-b). Animal Source Food (ASF) and the N feed conversion ratio (FCR) had an increasing shape with significant increase of ASF (> 5 kton N) only when N FCR was higher than ~12% (**Figure VI-2**a). Fodder Nitrogen Use Efficiency (Fodder NUE) and Nitrogen Self-Sufficiency (NSS) had a polynomial shape whereby higher Fodder NUE (> 80%) was associated with higher levels of NSS (> 80%) (**Figure VI-2b**). There were four synergies among performance and impact indicators (**Figure VI-2c-f**). N Surplus decreased (at ~20 $kgN.ha^{-1}$) with higher NSS (~75%) and with higher Fodder NUE (~75%). N Excretion Emissions also decreased (to 1.5 kgN.kgN ASF^{-1}) at varied levels output of ASF (from 5 to 20 kton N) and with higher N FCR (~12%). Distribution of departments was homogeneous.

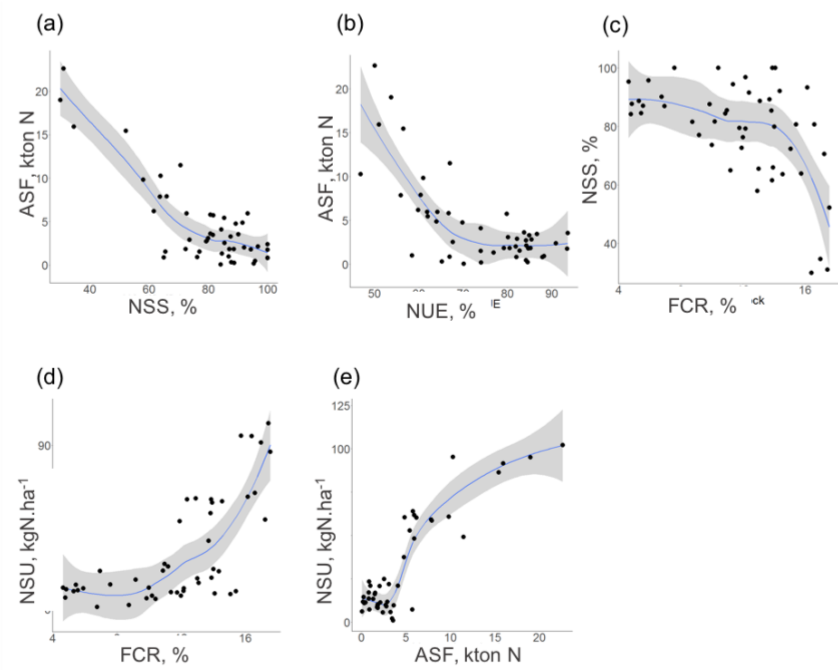

Figure VI-3. Tradeoffs among performance (a-c) and among performance and impacts (d-e) in 48 livestock dominated NUTS3 units. ASF: Animal Source Food; FCR: Nitrogen Feed Conversion Ratio; NUE: Fodder Nitrogen Use Efficiency; NSS: Nitrogen Self-Sufficiency; NSU: Nitrogen Surplus.

There were three trade-offs among performance indicators (**Figure VI-3a-c**). The relationship between NSS and ASF had a decreasing convex shape and showed that higher output of ASF (> 10 kton N) came at the expense of reduced NSS (~ < 60%). Fodder NUE and ASF, had a decreasing convex shape and showed decreasing output of ASF (< 10 kton N) with increasing levels of Fodder NUE (> 60%). Distribution of departments along the curve was homogeneous. N FCR and NSS, had a decreasing concave shape and showed that NSS was decreased (> 80%) at increased levels of N FCR (> 14%). Distribution of departments was homogeneous. There two trade-offs among performance and impact indicators (**Figure VI-3d-e**). N Surplus and N FCR had a convex increasing shape showing increased N Surplus (> 30 kgN.ha^{-1}) with higher levels of N FCR (> 12%). N Surplus and ASF had an increasing plateau-concave shape and showed rising N Surplus (> 25 kgN.ha^{-1}) with growing output of ASF (> 5 kton N). Departments' distribution concentrated at lower levels of N Surplus and ASF.

The spatial variation of synergy and trade-off decomposition

Mapping the four quadrants of each bagplot revealed distinct geographical patterns, and allowed to spot regions with better or worse performance and impacts.

Within synergistic relations such as ASF versus N FCR (**Figure VI-4a**), regions with 'superior' positioning were mostly identified in the West of France, and better performance was achieved because of higher levels of ASF output at high N FCR, which contributed to lower N Excretion Emissions per output unit (**Figure VI-4e-f**). However, these regions showed inferior positioning for the synergies related to lower performance of Fodder NUE and NSS and high N Surplus (**Figure VI-4b-c-d**). Conversely, Eastern-Central regions showed superior positioning, because they were mainly dominated by grasslands and had higher levels of Fodder NUE, NSS, thus lower N Surplus.

In trade-offs relations, mapping interactions revealed the marked conflict within pairs of variables, such as N FCR versus NSS, with only a few departments (27%; n= 13) in superior positions (**Figure VI-5a**). The conflict was further accentuated in trade-offs between indicators of livestock performance and environmental impact, such as in ASF versus N Surplus, that showed only 10% of superior cases (n=5), which highlighted how unlikely regions are to reach high levels of ASF output without high N Surplus (**Figure VI-5e**). The conflict/antagonism in trade-offs was also visible with the high predominance of intermediate positioning in all interactions of **Figure VI-5**. Intermediate positioning appeared on average in more than 70% of departements (n= 34), thus showing that gains in one indicator was achieved at the expense of loss on another.

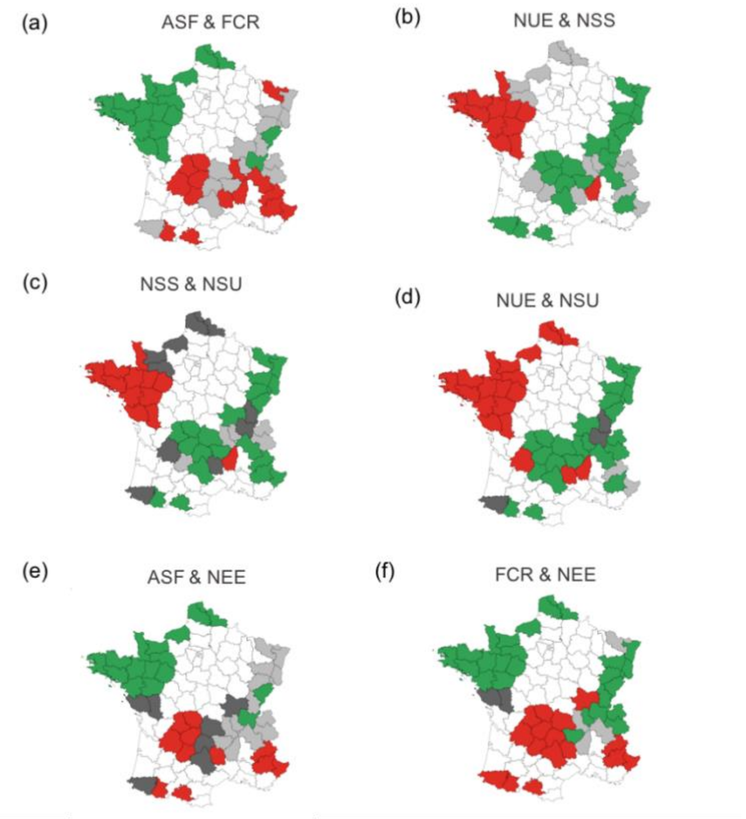

Figure VI-4. Spatial decomposition of synergies among performance (a-b) and among performance and impacts (c-f) in 48 livestock dominated NUTS3 units. Green: Superior; Red: Inferior; Grey: Intermediate. ASF: Animal Source Food; FCR: Nitrogen Feed Conversion Ratio; NUE: Fodder Nitrogen Use Efficiency; NSS: Nitrogen Self-Sufficiency; NEE: N Excretion Emissions; NSU: Nitrogen Surplus.

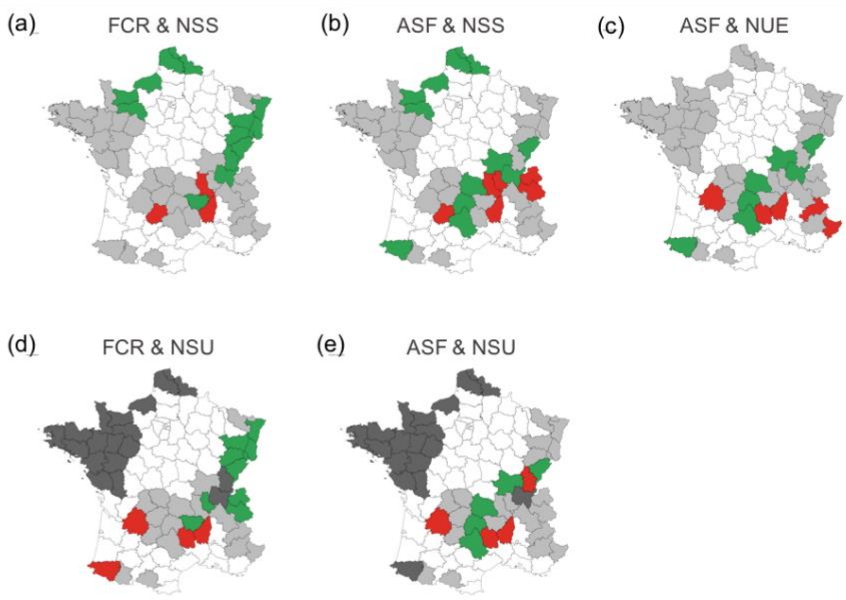

Figure VI-5. Spatial decomposition of tradeoffs among performance (a-c) and among performance and impacts (d-e) in 48 livestock dominated NUTS3 units. Green: Superior; Red: Inferior; Grey: Intermediate. ASF: Animal Source Food; FCR: Nitrogen Feed Conversion Ratio; NUE: Fodder Nitrogen Use Efficiency; NSS: Nitrogen Self-Sufficiency; NSU: Nitrogen Surplus.

Typology of interactions

A principal component analysis (PCA) upon counts of each category (superior, inferior and intermediate positioning) followed by a hierarchical cluster analysis (HCA) lead four groups of departments. The PCA conducted on the set of data resulted in the identification of two factors with an eigenvalue > 1. These factors explained 46.2% and 38.6% of the total variance. Factor 1 was positively related to superior positions of trade-offs and negatively related to inferior positions of synergies. Factor 2 was positively related to inferior positions of trade-offs and mostly negatively related superior positioning of synergies. **Figure VI-6** shows the projection of these four classes on the first and second factors of the PCA. **Figure VI-7** shows the projection of the classes on a NUTS3 level map of the studied departments of France.

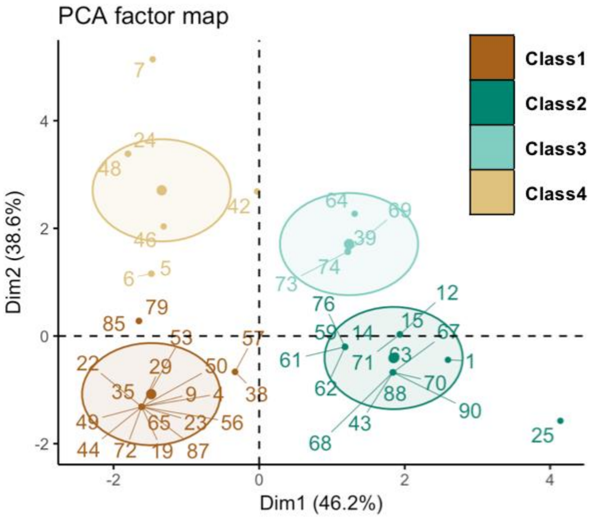

Figure VI-6. Projection of four classes on the first and second factors of the PCA.

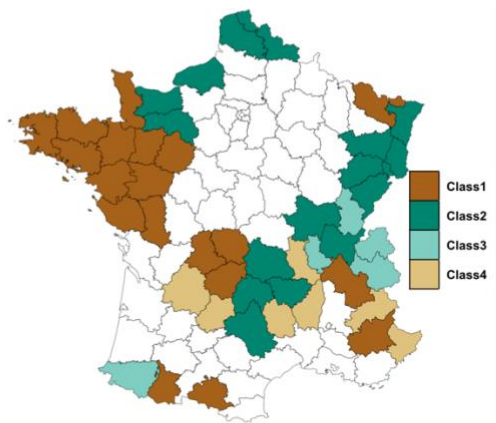

Figure VI-7. Projection of four classes resulting from HCA upon results of decomposition of synergies and trade-offs on a NUTS3 level map of France.

Class 1 (C1; n = 19) included departments characterised by intermediate positioning in all the cases of trade-offs, which was defined by a high value for one indicator and low value for another indicator. 60% of the departments in C1 were located in Western France and had very intensive livestock production systems, with higher performance in terms of N FCR and ASF but lower performance in NSS and Fodder NUE as well as high impacts associated with large N Surplus. C1 also included departments of the northern border of Massif Central and mountainous regions (French Alps and Pyrenees). These departments were characterized by lower performance in terms of N FCR and ASF but higher performance in NSS and Fodder NUE as well as lower impacts associated with large N Surplus.

Class 2 (C4; n = 14) included departments that were mostly characterised by superior positions in cases of trade-offs. Compared to other classes, departments in C2 also appeared more frequently in superior positions in the synergies studied. These departments were distributed in the North, East and Centre of France. Overall interactions among performance and impacts indicators for C2 ranked higher (performance indicators were higher than for the other classes, and impacts lower) because of higher efficiency of both Fodder NUE and N FCR, and higher levels of NSS along with lower N emissions and N surplus, thus high environmental quality.

Class 3 (C3; n = 5) included departments that were characterised by intermediate positioning in most of the cases of synergies, which was defined by high value for one indicator and low value for another. Compared to other classes, departments in C3 also appeared less frequently in inferior positions in all synergies studied. Intermediate positioning were mainly characterised by a combination of good performance in impact indicators and Fodder NUE, N FCR along with poor performance in NSS and ASF indicators.

Class 4 (C2; n = 7) included departments that were mainly characterised by inferior positions in cases of trade-offs, which was defined by low values for both indicators of the interaction. Compared those of the other classes, departments in C4 also appeared more frequently in inferior positions for all the synergies studied. Overall interactions among performance and impacts indicators for C4 departments were ranked very low because of marginal livestock production, with low efficiency rates along with poor environmental quality.

Discussion

Factors driving trade-off and synergy patterns

The observed spatial heterogeneity in livestock areas reflected the different types of interactions between performance and impact indicators, characterized by synergies and trade-offs, arising from a diversity of livestock farming systems in these areas. The spatial decomposition of synergies and trade-offs was followed by a classification that evidenced 4 groups. The C1 class, mainly formed by departments in Western France, was specialised in intensive livestock production systems, characterized by large monogastrics populations, high concentrates diets, and high stocking rates. Specialisation enabled higher performance in terms of feed conversion efficiency and provision of ASF, but it furthered the dependency on global feed protein, and raised environmental concerns due to the large amounts of manure generated by landless systems with limited agricultural area available for spreading. In context of several European regions (Flanders, the Netherlands and Brittany), Coelli et al. (2007) reported that high stocking rates resulted in volumes of nutrient excretion far higher than fertilisation recommended rates, thus resulting in high nutrient surplus, potentially contributing to eutrophication and acidification. Nevens et al. (2009) established some targets of N Surplus necessary to comply with environmental guidelines (European Nitrates Directive) for dairy farms in the Flanders at 150 kg N ha-1 year-1, which is above the values we observed in our study (for C1 they amounted to 47 ± 35 kg N ha-1). Nevertheless, caution is needed as different soil conditions can imply different target values, and the essential aspect to note in our analysis is that a higher environmental risk (linked to higher N Surplus) is associated to regions holding high stocking rates with larger share of monogastrics fed exclusively on concentrates.

Comparing C1 and C2 departments, it seemed the equilibrium of transition, from intermediate to superior positioning, respectively, relied on livestock related drivers. In this study the coexistence of higher performance and low environmental impacts (C2, superior positioning), was linked to lower levels of stocking rates, a higher share of forage in the diet and larger share of ruminants in the livestock population. These findings corroborate to principles of agroecology, that suggest the reconnection of livestock to cropping systems to benefit from the recycling of nutrients, and lessen the dependence on external resources (Dumont et al., 2013; Soteriades et al., 2016). In our case, C4 departments illustrated well this concept, in the sense that lower stocking rates (1.07 LU.ha-1), production primary emphasised on dairy, and a balanced land use pattern (even area allocated to fodder and crop) have jointly contributed to improved performance, reaching high levels of efficiency and self-sufficiency and relatively low environmental impacts. In prior study, van Zanten et al. (2016) assessed the role of livestock in future food supply and quantified the land use efficiency for laying hens and dairy cows. They found that ruminant systems valued better marginal land than monogastrics, and were even more efficient to produce human-edible protein than crops. Although we have not implicitly evaluated land suitability for crop production, our study also pointed to a better overall performance (superior positioning) of regions (C4) located in mountainous areas which involves dairy production on grazing systems.

Mixed effects of intensification

In a review of past research on the nexus between livestock and environment, Herrero et al. (2015) pointed to significant focus on sustainable intensification, with the development of methods for assessing environmental impacts, and highlighted the importance of assessing efficiency as means of reducing environmental impact. Mainstream approaches yielded indicators of efficiency derived from life cycle assessments, which often referred GHG emissions to livestock unit produce. Traditional product-based scope tended to favour livestock product originating from intensive systems since they are characterized by higher yields per unit of farm area or LU, and the performance indicators directly scale with yields. Our findings also reflected this trend, as the synergy in **Figure VI-2e** showed the higher the ASF output the lower the levels of N excretion emissions per unit produce. Although impacts measured per unit produce had a synergistic relationship and characterised superior positioning for C1 departments, the impact measured per unit of land (N Surplus per ha of fodder area) revealed a conflicting relationship and showed an opposite trend: the higher the ASF output, the higher the on-farm N surplus and the environmental impacts.

On recent study, Ross et al. (2017) also identified similar tendencies, and noted that while fat-protein-corrected milk yield was the main functional unit used in LCA studies of dairy production, results were prone to different interpretations when using additional function units, such as those related to land. This highlights the need to account for impacts from a multiple perspective, as conflicting patterns may exist, and gains in efficiency and production normally contribute to the reduction of GHG on a product basis, but can also mean potential environmental impact from a land basis perspective.

Comparison with other studies

Le Noë et al. (2017) studied N flows in agro-ecosystems at same level, and reported maximum N Surplus in grasslands of 108 kg N ha-1 year-1, which is close to maximum value found in our analysis of 102 kg N ha-1 year-1. The small gap could be attributed to the difference in the year of evaluation, 2006 and 2010, as well as differences in the accounting since silage maize was included in the fodder area here instead of the cropland area in Le Noë et al. (2017). Both values remain nevertheless comparable and reflect the imbalance introduced by high stocking rates to a relative small fodder area, leading to excess N applications in Brittany. The authors also identified in their results the trade-off between agronomic and environmental performance, and similar pattern of conflict in the computation of N losses per land area and per unit produce, which also corresponded to previously reports of Chatzimpiros and Barles (2013). Our approach to the N the metabolism brought a novel aspect as compared to Le Noe et al, as it presents a quantification of flows to the livestock pool rather than simply using it to close the N balance. This novelty contributes to better handle of the livestock metabolism and the effect of production systems variables on their performance. (thus making your typology more relevant in terms of farm and cattle management).

Regarding NSS and N Surplus indicators, Chatzimpiros and Barles (2010) highlighted the role played by grazing cattle in reducing the reliance on soybean imports, and limiting N losses, which is line with our findings and is exemplified by departments in the C2 class. The same authors pointed to livestock diets composition and origin of feed inputs as the main determinants of environmental impacts, and we provided more insight into this issue by bringing monogastrics into the analysis. Additional drivers of environmental performance were also evidenced, namely species composition (i.e. ruminants versus monogastrics), stocking rates and main production objective (milk versus meat).

Under starkly different climatic conditions in Australia, Stott et al. (2016) found in the dairy sector that decreasing N recovery and increased N losses to the environment were associated with increased milk productivity per unit area of farm land. They also underlined similar drivers of performance, the increased stocking rates, dependence on feed imports, and also pointed to structural and herd aspects linked to increased farm size and animals' productivity, respectively.

Added-value of the proposed methodology

The combined approach we proposed, by linking a material flow analysis in terms of nitrogen, then studying the interactions among performance and impact indicators, and decomposing the existing spatial heterogeneity at regional level, has brought new knowledge on livestock systems thinking. Our analysis revealed how livestock farming systems configuration influenced overall regional performance in the use of resources and impact to the environment. Most performing configuration characteristics, in terms of the six indicators we studied, suggested regions favouring a larger share of ruminants over monogastrics, emphasising dairy production on grazing at lower levels of stocking rate.

The question of performance and impact in livestock production have been addressed in several studies, mainly focusing dairy production, very often treated at animal and/or farm level. Our study helps building an answer for issues on sustainable livestock production, encompassing the four main reared species (cattle, small ruminants, poultry and pig), as it draws from an assessment based on real production cases, showing different patterns of regions performance. This provides knowledge (or a basis) for future research/action on the possibilities of re-configuration of drivers of performance, in order to steer regions towards optimal levels of efficiency in the use of resources and reduced environmental impacts.

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VII. LINKING CURRENT SOCIAL, ENVIRONMENTAL AND CULTURAL SERVICES PROVIDED BY LIVESTOCK TO PAST INTENSIFICATION TRAJECTORIES

Introduction

Recent studies highlighted the important role of agroecosystems in the provision of goods and services (GS). The contribution is a two-way street: agroecosystems depends on services provided by natural ecosystems (e.g. pollination, soil fertility, nutrient cycling), and agroecosystems also influence the provision of crucial services to society (e.g. conservation of biodiversity, water purification, carbon sequestration) (Power, 2010). Grasslands occupied by ruminant livestock covers nearly 2.0 billion ha and another 0.5 billion ha of arable land is need to produce feed, which together represents about half of the global agricultural land (Mottet et al., 2017). This evidences the close link between livestock and agroecosystems and indicates that livestock plays a major role in GS provisioning.

Provision of GS refer to the benefits people obtain from ecosystems, which contributes to their well-being, and are classified in four categories: provisioning, regulating, cultural and supporting (Millennium Ecosystem Assessment, 2005; Costanza et al., 2017). Provisioning services are associated to production of food, feed, fuel, fibre and wood. Regulating services are associated to climate, flood and disease regulation as well as water purification. Cultural services relate to aesthetic, spiritual, educational and recreational characteristics. Supporting services are linked to nutrient cycling, soil formation and primary production aspects. Services and goods can occur in the form of bundles, which are sets of ecosystem services that repeatedly appear together across space or time (Raudsepp-Hearne et al., 2010).

Different bundle composition means different levels of service provision, and the lower level or lack of one particular service can be related to an alteration of agroecosystem health. Foley et al. (2005) report on the challenge of meeting human needs and maintaining the capacity of ecosystems to provide GS in the future. The authors stress the need to reconcile agricultural production with regulating and supporting services, in view of maintaining the long-term capacity of systems to provide GS. This need calls for assessments dealing with trade-offs and synergies among provisioning, regulating, cultural and supporting services.

Ryschawy et al. (2017) analysed the provision of GS derived from livestock across regions in France, and found four major types of bundles varying from depleted bundles (very low GS provision) to multifunctional bundles (balanced levels among GS). Their contrasting composition reflected regional differences of livestock systems that contributed in diverse forms to the provisioning of GS. Although the study provides an account on the multiple benefits provided by the livestock sector, there is no information on drivers that contributed to regional differentiation of bundles. This highlight the need of understanding how socio-economic, political and biophysical drivers determined the composition of bundles in different regions.

The objective of this study was to understand the influence of past intensification drivers (physical, technological, and economic) on the current provision of social, environmental and cultural services by the livestock sector in France. We used a set of multivariate methods to analyse simultaneously changes in production intensity from 1938 to 2010, and the current level of provision of social, environmental and cultural services provisioning. Our analysis focused on a set of 60 French departments where the livestock sector plays a significant role.

Material and Methods

The influence of intensification trajectories on the current provisioning of environmental, cultural and rural vitality services by the livestock sector was assessed at department level. From a total of 95 French metropolitan departments, a subset of 60 was selected according to the livestock specialization coefficient of each department. Livestock specialization coefficient was calculated as the proportion of total NUTS 3 farms that were livestock farms. Departments with a coefficient of livestock specialization above 0.5 were selected; above this threshold we considered that livestock plays a role on services provision through its link to land and resources use.

Two data sets were used to describe intensification trajectories and service provision. The first data set characterized changes in the process of intensification between 1938 and 2010. It included three categories of variables describing: livestock, land use and socioeconomic dimensions (**Table VII-1**) and already used for our first analysis (see ref to the section where the data set is described).

Table VII-1. Variables considered in the analysis of change in the intensification process of the livestock sector.

Variables	Units
Livestock variables	
Herbivore stocking rate	$LU.ha^{-1}$
Monogastric stocking rate	$LU.ha^{-1}$
Herbivore meat production per main fodder area (cattle, sheep, and goat meat)	$kg.ha^{-1}$
Milk production per main fodder area (cow, sheep, and goat milk)	$kg.ha^{-1}$
Land-use variables	
Share of utilised agricultural area in the department	-
Share of main fodder area in utilised agricultural area	-
Socioeconomic variables	
Average farm size	ha
Labour productivity	$ha.AWU^{-1}$
Dependence ratio (purchased feed/ final livestock output)	-
Tractor density	$tractors.ha^{-1}$

To make meaningful comparisons among intensification variables and detect the direction and rate of change in the intensification process between 1938 and 2010, each numeric variable was divided by its average department value. The rate of change was calculated subtracting 1938 from 2010 observations. Variable values equal or close to zero meant the rate of change was similar to the average department. Negative variable values meant the rate of change was lower than observed in the average department. Positive variable values meant the rate of change was higher than observed in the average department.

The second data set characterized the provision of services by the livestock sector and was organized in three categories of variables: rural vitality, environmental and cultural (**Table VII-2**). The rural vitality category included variables related to employment in livestock farms, in the agro-food industry and the contribution of the sector to overall employment. This category provides an account of the economic relevance of the livestock sector, which in Europe represents 42% of the total agricultural activity and provides employment to nearly 30 million people (Livestock, 2017). The environmental category included variables related to high nature value areas i.e. areas sustaining high levels of biodiversity (add ref to HNV), grasslands bird biodiversity (Teillard et al., 2015) and water quality. This category includes variables that account for aspects about the multifunctionality of farming systems, associated to the maintenance of habitat diversity and wildlife, and supporting services like nutrient cycling and water purification (Andersen et al., 2003; Power, 2010). The cultural category included variables related to heritage landscapes, agrotourism and heritage animal products. Although cultural services consists on immaterial benefits provided , they can be directly experienced and intuitively appreciated by people, such as aesthetic, social relations, recreational and heritage aspects (Plieninger et al., 2013). Data for service provisioning variables were developed by Ryschawy et al. (2017). The reference year was 2010.

Table VII-2. Indicators selected to characterize services provided by the livestock sector. Adapted from Ryschawy et al. (2017).

Services	Indicator	Code	Unit
Rural vitality			
Employment in livestock farms	Workforce on livestock farms	EmpFarm	AWU
Employment in livestock agrofood industry	Employees in livestock agrofood industry	EmpInd	Number
Contribution of livestock to employment	Contribution of livestock sector to overall employment	Employ	%
Environmental			
High Nature Value of landscape	Area classified as High Nature Value	HNV	% UAA
Conservation of biodiversity	Proportion of grassland birds in bird community	Biodiv	%
Water quality	Proportion of municipalities outside nitrate vulnerable zones	Water	%
Cultural			
Heritage landscapes	Areas in heritage landscapes (grassland, specific areas, and trees)	Landscape	%
Agrotourism	Proportion of farms practicing agrotourism	Agrotourism	%
Heritage animal products	Number of quality-labelled animal products (SIQO)	Product	%

* AWU: Annual work unit; UAA: Utilized agricultural area

Statistical analysis

The analysis of the relationship between the intensification process and the provision of services by the livestock sector included three major steps: principal component analysis (PCA), co-inertia analysis, and a hierarchical cluster analysis (HCA). These three major steps are preceded by study of the correlation coefficients between variables of first and second data sets, for identification of interactions between the two data sets. The three major steps are explained, as follows:

First, a PCA was performed on the first and second data sets, to reduce the number of variables while keeping the largest possible variance. In the first data set four components were retained, explaining 72% of the total variance (eigenvalue >1). On the second data set three components were retained and explained 80% of the total variance (eigenvalue >1). The two PCA generated two tables that were used as inputs to the second step of the statistical analysis.

Second, a co-inertia analysis was performed on the two tables. The co-inertia analysis enable simultaneous analysis of two tables, and identifies the underlying data structure, and relationships between them (Dolédec and Chessel, 1994; Dray et al., 2003). It finds ordinations from the two data sets by similarity, by searching successive orthogonal axes from the two data sets with maximum squared co-variance. A complementary Monte Carlo permutation test follows the co-inertia analysis, to verify the significance of co-structure between tables. It was carried out on the two tables for 1000 permutations.

Third, a HCA was performed on the normed row scores, which is an output of co-inertia analyses. Complying with the Euclidean distance and Ward's aggregation method the HCA generated three groups of departments. Results presented in the form of tables, graphs and maps, were computed using the R software package (R Core Team, 2015). An analysis of variance (ANOVA) followed by the Tukey's test was performed on results related to changes in the intensification process and provision of services.

Results

According to the Kaiser criterion (eigenvalue > 1) two axis of the co-inertia analysis were kept, which explained 93% of the total variance. the Monte Carlo test revealed a high degree of co-structure between the two tables (RV coefficient = 0.57; p-value < 0.05) suggesting a relationship between intensification trajectories and services provisioning.

The high degree of co-structure resulted from a number of correlations between variables in the two tables (**Table VII-3**). Moderate to strong correlations occurred 17 times out of 90 correlations (10 variables in table 1 times 9 variables in table 2). Ten correlations referred to livestock related variables:

- The provision of heritage landscapes (Landscape) and employment on livestock farms (Emp Farm) was positively correlated with Herbivore stocking rate.
- The provision of employment at both farm and agro-food industry (Emp Farm; Emp Ind) were positively correlated to Monogastric stocking rate and Milk productivity; although it was observed negative correlation between water quality (Water) and Monogastric stocking rate and Milk productivity.
- The provision of high nature value areas (HNV) and water quality was negatively correlated Herbivore meat productivity.

Five correlations referred to land use related variables. The share of the fodder area was positively correlated to the provision of heritage landscapes, conservation of biodiversity, water quality and the contribution of livestock to employment (Employ). It showed strong correlation with high nature value areas. Two correlations referred to socioeconomic variables. The dependence ratio (i.e. inverse of self-sufficiency) was positively correlated to the provision of employment in livestock farms and in the agro-food industry.

Table VII-3. Correlation coefficients between intensification and services provisioning variables from French departments.

		Cultural			Environmental			Rural vitality		
		Agrotourism	Landscape	Product	Biodiversity	HNV	Water	Employ	Emp Farm	Emp Ind
Livestock	Herbivore SR	-0.01	**0.68**	0.19	0.36	0.28	0.23	0.46	**0.52**	0.09
	Monogastric SR	-0.26	0.02	-0.42	-0.25	-0.43	**-0.57**	0.25	**0.52**	**0.78**
	Meat productivity	-0.26	-0.23	-0.02	-0.45	**-0.59**	**-0.58**	-0.12	0.13	0.38
	Milk productivity	-0.22	0.03	-0.41	-0.16	-0.49	**-0.58**	0.24	**0.53**	**0.70**
Land use	Share of UAA	-0.25	-0.02	0.11	-0.10	-0.31	-0.24	0.38	0.06	-0.09
	Fodder area : UAA	0.24	**0.64**	0.06	**0.59**	**0.71**	**0.56**	**0.50**	0.44	-0.04
Socioeconomic	Average farm size	-0.20	0.08	0.20	-0.00	0.02	-0.03	0.08	0.11	0.20
	Labour productivity	-0.13	0.01	0.09	0.11	0.14	0.18	0.06	-0.14	-0.14
	Dependence ratio	-0.17	0.30	-0.09	-0.19	-0.18	-0.32	0.22	**0.50**	**0.57**
	Tractors density	-0.14	0.38	-0.07	0.23	0.06	0.06	0.39	0.42	0.34

Agrotourism: Proportion of farms practising agrotourism; Landscape: Areas in heritage landscapes (grassland, specific areas, and trees); Product: Number of quality-labelled animal products (SIQO); Biodiv: Proportion of grassland birds in bird community; HNV: Area classified as High Nature Value per km^2; Water: Proportion of municipalities outside nitrate vulnerable zones; Employ: Contribution of livestock sector to overall employment; EmpFarm: Workforce on livestock farms; EmpInd: Employees in livestock agrofood industry

Figure VII-1 shows plots derived from co-inertia analysis on the two data sets of intensification and services provisioning variables. **Figure VII-1a** shows the variables that had higher correlation with these two axes. First axis was positively correlated with monogastric stocking (Mon SR) rate and milk productivity (Milk prod), and negatively correlated with environmental variables (Water, HVN, Biodiv). Second axis was negatively correlated to the share of fodder area (MFA:UAA) and herbivore stocking rate (Herb SR), and to the provision of employment in livestock farms (Emp farm), the contribution of livestock to overall employment (Employ) and to the provision of heritage landscapes (Landscapes). **Figure VII-1b** illustrates the French departments plotted in these two axes. The hierarchical cluster analysis revealed three groups (**Figure VII-1c**) which are projected on a NUTS3 map of France (**Figure VII-1d**).

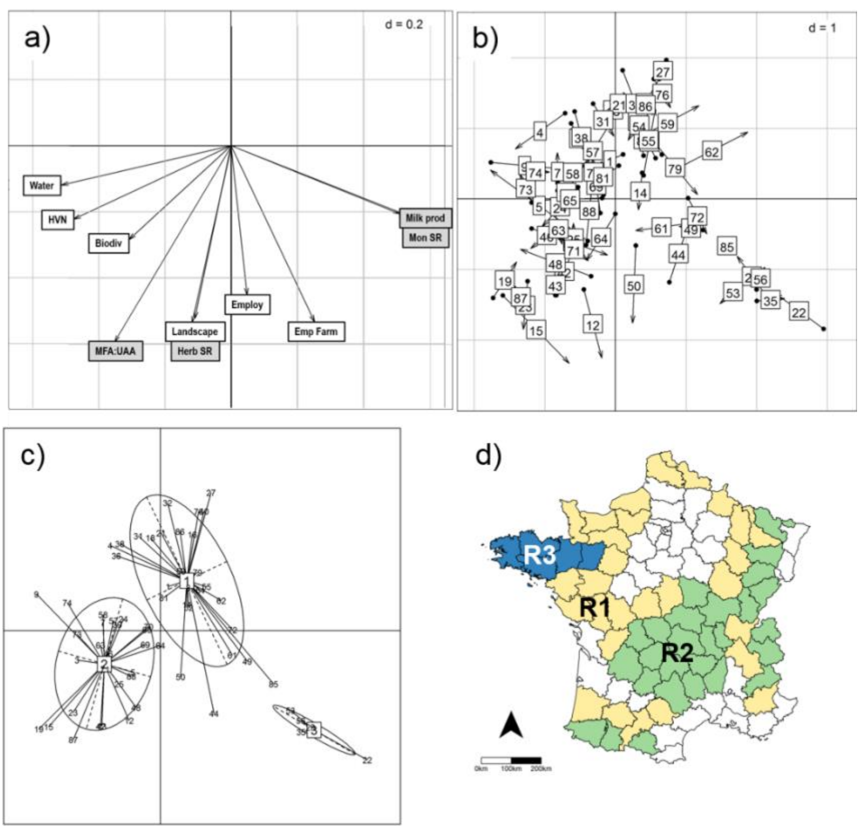

Figure VII-1. Co-inertia analysis results followed by classification. a) Projection of intensification and services provisioning variables most correlated with co-inertia analysis axis 1 and axis 2. b) Projection of French departments scores after co-inertia analysis. Boxes filled in grey color are related to intensification variables and boxes filled in white color are related to services' variables. c) Projection of the three groups on the first and second axes of the co-inertia analysis after the hierarchical cluster analysis. d) Location of the three groups of French departments. R1, R2 and R3 correspond to 'Mixed-crop livestock areas', 'Extensive livestock areas' and 'Intensive livestock areas', respectively.

Table VII-4 presents the absolute values of variables and the % rate of change.

Table VII-4. Trends of change in the French departments per group: 'Mixed-crop livestock areas', 'Extensive livestock areas' and 'Intensive livestock areas'.

Variables	Year	Mixed crop-livestock areas n = 28	Extensive livestock areas n = 27	Intensive livestock areas' n = 5	Average n = 60
Herbivore SR	1938	0.49 b	0.48 b	0.68 a	0.50
	2010	0.72 c	0.93 b	1.28 a	0.86
	% change	48%	95%	89%	73%
Monogastric SR	1938	0.10 b	0.13 ab	0.16 a	0.12
	2010	0.24 b	0.09 b	1.80 a	0.30
	% change	149%	-28%	1045%	160%
Meat productivity	1938	64 a	63 a	74 a	65
	2010	158 a	86 b	201 a	129
	% change	145%	36%	171%	100%
Milk productivity	1938	778 a	628 a	907 a	721
	2010	2142 b	1168 c	5000 a	1942
	% change	175%	86%	451%	169%
Share of UAA	1938	65% a	52% b	73% a	60%
	2010	57% a	43% b	63% a	51%
	% change	-12%	-17%	-14%	-14%
Share of fodder area	1938	63% a	68% a	59% a	65%
	2010	43% b	77% a	59% b	60%
	% change	-32%	13%	0%	-8%
Average farm size	1938	19 a	14 b	12 b	16
	2010	72 a	56 b	48 b	63
	% change	272%	295%	315%	284%
Labour productivity	1938	11 a	08 b	07 b	9
	2010	48 a	41 ab	30 b	43
	% change	348%	396%	341%	367%
Dependence ratio	1938	0.14 a	0.14 a	0.15 a	0.14
	2010	0.26 b	0.23 b	0.44 a	0.26
	% change	84%	65%	199%	86%
Mechanisation *100	1938	0.11 a	0.06 b	0.03 b	0.08
	2010	0.48 a	0.55 a	0.60 a	0.52
	% change	341%	784%	1881%	540%

Means followed by same letter within a row do not significantly differ by Tukey's test (P<0.05). Indicators are expressed as the mean of all departments belonging to each group.

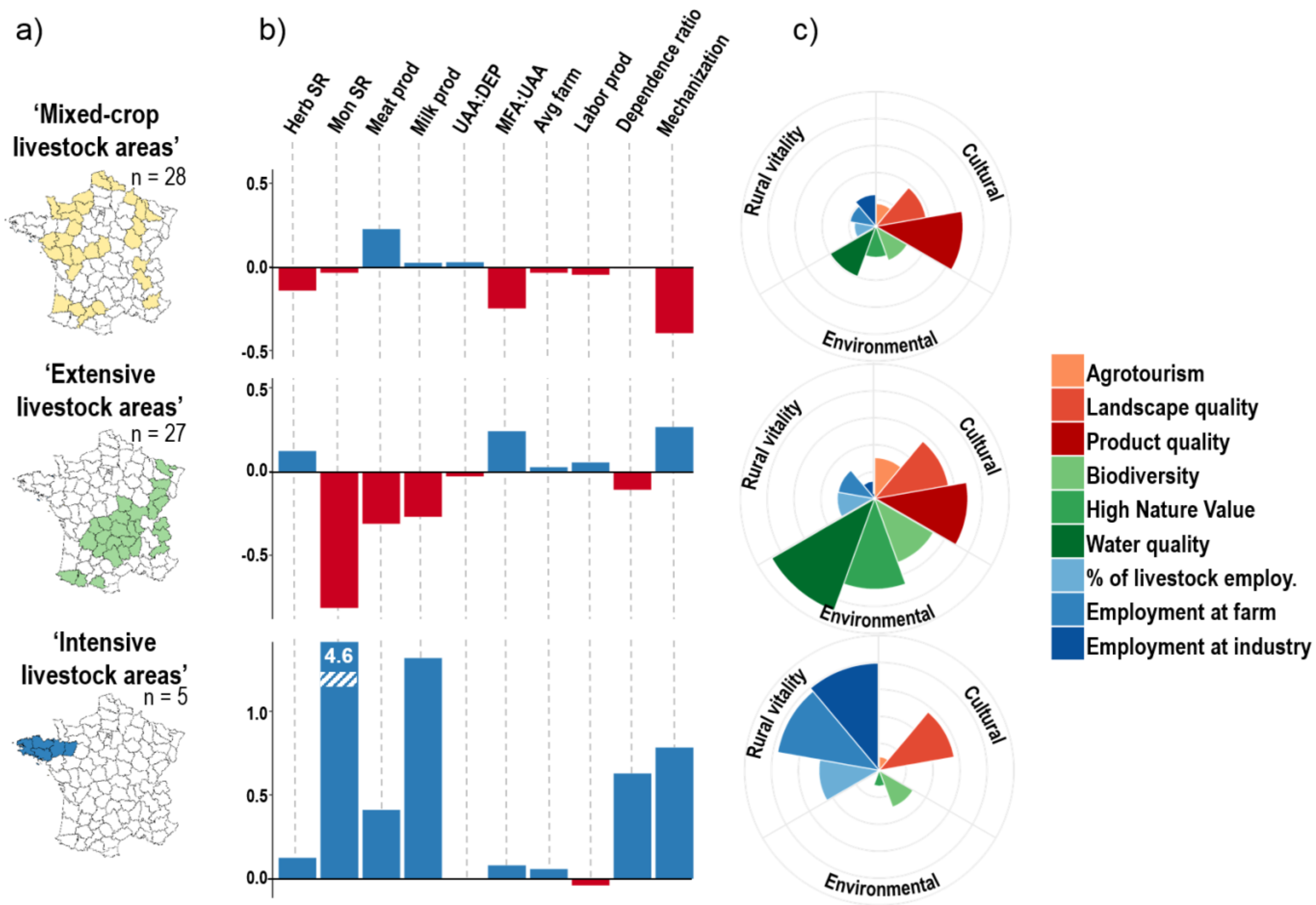

Figure VII-2. Spatial trends of change in intensification variables and current provisioning of services. a) Location of the three groups of French departments, 'Mixed-crop livestock areas', 'Extensive livestock areas' and 'Intensive livestock areas'. b) Average rate of change of intensification variables in three groups of French departments (blue bars indicate the rate of change was higher than in an average department and red bars indicate the rate of change was higher than in an average department and red bars indicate it was lower). c) Average provision of services per group of French departments.

Figure VII-2 displays bar charts illustrating the rate of change for intensification variables per group of departments, and polar charts showing the corresponding bundle[8] of services provided in each group.

'Mixed-crop livestock areas' (R1; n = 28) mainly included departments located on the surrounding area of the Paris basin and few in the South-West and South-East of France, and was characterized by smooth rates of change (Table 26). Compared to an average department, R1 departments had lower rates of change of herbivore stocking rate (48%), and share of the fodder area (-32%) and of mechanization (341%). R1 had similar rate of change of an average department for monogastric stocking rate (149%), milk productivity (175%), share of utilized agricultural area (-12%), average farm size (272%), labour productivity (348%) and dependence ratio (84%). The only variable that had considerably higher rate of change compared to an average department was the herbivore meat productivity (145%). The provision of services showed low levels of all types of services, except for heritage animal products. The fact that this group has passed through smooth changes in the process of intensification, explains the minor provision of services by the livestock sector. The geographical proximity with crop specialized departments on the North and with departments emphasizing grazing on R2, characterizes a transition frontier where livestock loses importance, either in aspects of lower stocking rates of animals, and retraction of main fodder area.

'Extensive livestock areas' (R2; n = 27) mainly included departments located in the French Massif Central and in the East, and was characterized by contrasted rates of change. Compared to an average department, R2 departments had lower rates of change meat productivity (36%), milk productivity (86%), and in the dependence ratio (65%). The decreased monogastric stocking rate (-28%) was markedly opposed to the average increase rate observed in all departments. R2 had similar rate of change of an average department for share of utilized agricultural area (-17%), the average farm size (295%) and the labour productivity (396%). R2 presented rates of change considerably higher compared to an average department for herbivore stocking rate (95%), the share of the

[8] Raudsepp-hearne et al. (2010) defines a bundle of services as sets of ecosystem services that repeatedly appear together across space or time.

fodder area (13%) and mechanization (784%). The provision of services showed the most balanced pattern of services compared to other groups. Although low levels of vitality services were observed, cultural and environmental services were provided at the highest levels among groups. Increased rates of changes favoring herbivores over monogastrics, along with increased share of the main fodder area have played an important role on environmental services. Although R2 had lower levels of meat and milk productivity compared to other groups, it had the highest level of heritage animal products, which in this case indicates that quality compensate for quantity of animal products. R2 also showed high levels of heritage landscape and the highest level of farms practicing agrotourism.

'Intensive livestock areas' (R3; n = 5) included Western French departments, and were characterized by the highest rates of change. Compared to an average department, R3 departments had slightly higher rates of change in herbivore stocking rate (89%), share of fodder area (0%) and average farm size (315%). Nevertheless, this rates of change were minor compared to marked increased rates of change in monogastric stocking rate (1045%), meat productivity (171%), milk productivity (451%), dependence ratio (199%) and mechanization (1881%). In this group, all livestock related variables had higher rates of change compared to an average department. R3 had similar rate of change of an average department in the share of the agricultural area (-14%) and labour productivity (341%). The provision of services was mainly characterized by high levels in the vitality services (related to employment), and to a lesser extent to the provision of heritage landscapes. Environmental and remaining cultural services showed very low levels, notably for the provision of water quality and heritage animal products. The higher rates of change in the intensification process, specifically monogastric stocking rate and milk productivity, allowed the development of livestock sector in these departments, contributing to large employment opportunities. However, the concentration of very intensive production systems, at high stocking rates, and increased dependence ratio (purchased feed) lead to manure management issues, thus overall depleted environmental quality.

Discussion (*in preparation*)

Our analysis revealed that the provision of social, cultural and environmental services was spatially structured and based on three groups, determined by different rates of change in intensification variables over time. Mixed crop-livestock areas were mainly defined by smooth changes, with close variation to national averages, which resulted in low provision of services. Extensive livestock areas were mainly defined by higher rates of change on variables related to specialization on grazing (herbivores and fodder area), and lower rates of change on productivity aspects. This contributed to provision of high levels of environmental and cultural services, such biodiversity conservation and product quality labels. Intensive livestock areas were mainly defined by high rates of change related to the intensification of livestock production – high stocking rates and productivity, which contributed to of high levels of vitality services, such as high employability in both farm and industry.

How changes in the process of intensification influenced spatially differentiated provisioning of services?

The process of intensification played an essential role on the differentiation of livestock areas in terms of provision of social, environmental and cultural services. Changes in livestock productivity were the main positive determinants of rural vitality. But changes in livestock productivity influenced negatively the provision of environmental services. Changes in the fodder area influenced to a large extent the provision of environmental services, played a role in heritage landscapes, and had a positive contribution relative to overall employment. Although socioeconomic changes were very marked in absolute terms, they did not influence in a clear way the provision of services; with exception to changes in dependence ratio that went together with employment in farm and industry.

As changes in the intensification process were spatially differentiated, the current provision of services by the livestock sector also reflected the heterogeneous patterns of change. The three groups identified showed that regional differentiation patterns in the intensification- determined by different drivers, contributed to the formation of three distinct bundles.

Ranking drivers of changes

Biophysical drivers determined significant changes in land use cover, characterized by the conversion of grasslands into cropland in the plains ('Mixed crop-livestock areas'). In areas where such change was not possible because of limited agronomic potential (marginal and mountainous areas), the alternative consisted on emphasizing on grazing, as observed in the 'Extensive livestock areas' (Massif Central and Eastern France). The prominence of grazing systems, marked by lower stocking rates and lower productivity levels, influenced the provision of services in a more equilibrated pattern. The maintenance of grasslands played essential role in the conservation of biodiversity, as it supported higher share of birds that depend on this type of habitat to complete their life cycle (Henle et al., 2008). Teillard et al. (2017) highlights that increased biodiversity is achieved with optimal extensification, thus corroborating to our findings concerning the role of grasslands habitats in maintaining biodiversity. It also influenced water quality as grasslands provides continuous soil surface cover, and when managed at low levels of inputs and stocking rates, has positive contribution to water filtering (Hooda et al., 2000).

The specialization in 'Intensive livestock areas' were possible thanks to initial orientation of livestock production and because of higher share of rural population in 1938, thus high availability of workforce (Gambino, 2014). The monogastric population surged and lead to increased stocking rates, about a 1045% change over the period, which contributed to the development of employments in the livestock sector. There was an important movement of modernization in these areas (Brittany) based on technological rationalism and collective development. It enabled increased productivity and were followed by the development of upstream and downstream supply chain, i.e. feed and food industry (Lang et al., 2015). If this advances contributed to high levels of rural vitality services, it also had a negative impact on the environment. The large number of monogastrics along with dairy cows kept in landless systems is certainly the main driver of increased livestock productivity, that was essential in terms of high provision of ASF, but created issues related to manure management. Increasing quantities of manure in a limited area for spreading resulted in over fertilization of agricultural areas with consequent high losses to water streams, thus depleting water quality.

Levers of action to achieve/improve services provisioning equilibrium in livestock areas

- Identify areas with desirable patterns/bundles of ES and analyse in depth their characteristics (e.g. lower levels such as SAR and farm)
- Identify management practices that influence positive interactions among services and enhance multiple services simultaneously (Egoh et al., 2008) (Morelli et al., 2017)
- Design strategies to level off dis-services, and strategies to conciliate balanced levels for provisioning and regulating services

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IX. RESUME EN LANGUE FRANÇAISE

Décomposition et hiérarchisation des déterminants physiques, technologiques, et économiques des trajectoires d'intensification de l'élevage Français

Lors du dernier siècle, l'élevage Français a connu une importante intensification caractérisée par des différents changements à travers le pays. Particulièrement, la France a passé d'un état homogène avec la plupart de la surface agricole occupée par des prairies naturelles et une distribution uniforme des animaux, à un état hétérogène caractérisée par une distribution irrégulière de la part des superficies fourragères principales, les effectives animaux et la composition des espèces. Il est fondamental d'étudier les dynamiques des changements pour identifier les déterminants qui ont structurés les différentes trajectoires d'intensification et la configuration actuelle des territoires, aussi que de prédire les changements à l'avenir.

L'objectif de cette étude était de caractériser les trajectoires de l'élevage Français pour mieux comprendre le procès d'intensification par rapport aux changements socio-économiques, d'usage des terres et des facteurs liés à la production (technologiques). Un jeu de dix indicateurs a été utilisé pour analyser les changements majeurs entre 1938 et 2010, à l'aide d'une analyse en composantes principales, suivie par une classification hiérarchique ascendante pour 88 départements Français.

Entre 1938 et 2010 l'élevage Français a doublé sa capacité productive, grâce à des incréments dans la taille moyenne des fermes, à la mécanisation, aux gains en productivité du travail et en particulier à des fortes densités de stockage des monogastriques. Les changements les plus marqués au niveau national concerne en ordre décroissante : la mécanisation (les numéros de tracteurs par mil ha a passé de 1.2 à 5.3), la productivité du travail (quadruplé de 8.6 à 35.9 ha par unité de travail annuel), la production animale (à l'exemple de la production laitière, passant de 758 à 1856 litres par ha de superficie fourragère) et les densités de stockage (accrus de 0.57 à 0.98 UGB per ha). La classification hiérarchique ascendante nous a permis de capturer l'hétérogénéité dans les différents modes de changements, définis par un regroupement dans quatre trajectoires d'intensification. Deux trajectoires étaient formées par des départements ayant spécialisés en élevage, avec un type orienté dans des productions hors-sol intensives (ateliers laitier et monogastrique), et un deuxième type orienté vers les systèmes allaitants herbagers. Une troisième trajectoire corresponde à des départements qui sont spécialisés en culture, en ayant surtout un important niveau de productivité du travail, mais aussi ont maintenu des systèmes polyculture élevage à la marge du groupe de ces départements. La quatrième trajectoire correspond aux départements ayant les plus faibles niveaux d'effectifs et production animales. La hausse de la mécanisation dans la période étudiée a été importante et uniforme au niveau national, mais n'a cependant pas présentée des différences significatives entre les quatre trajectoires. Cette typologie de trajectoires d'intensification permettra de cibler des territoires spécifiques dans lesquels les impacts néfastes de l'élevage nécessitent d'être mitigés, aussi que des bonnes indications pour l'achèvement du développement durable de l'élevage Français.

Analyse des synergies et compromis entre les performances et impacts à l'environnement au sein des territoires d'élevage Français

L'élevage est un moteur majeur de l'usage des terres et des ressources et participe à la fourniture des services socio-économiques et de nutrition, dans les pays développés et en dans le pays en développement. On observe une grande diversité des systèmes de production agricoles liée à des éléments multiples, dont la combinaison de différents niveaux d'intensification, des différentes zones agroécologiques et d'objectifs de production divers. Cette diversité influent sur l'efficacité de l'usage des terres et des ressources (Herrero et al., 2015). À partir de la seconde moitié du XXe siècle l'intensification de l'agriculture a contribué à l'augmentation de la production des cultures et d'aliments d'origine animale par unité de surface et de temps. En parallèle se suit un découplage entre production animale et production agricole. Ceci a été défini par une séparation des zones de cultures dans les plaines des zones de montagne et des forêts utilisées pour le pâturage (Lambin et al., 2001). La spécialisation des territoires d'élevage a bénéficié des technologiques à haut rendement basés sur trois piliers, dont l'amélioration de la nutrition, de la génétique animale et le contrôle sanitaire (Gerber et al., 2015). Des rations alimentaires caractérisées par des aliments riches en énergie et en protéines rendait les systèmes de plus en plus dépendants des protéines produites à l'échelle mondiale. De ce fait, aujourd'hui l'élevage a une part importante dans le marché mondial des flux de protéine (Lassaletta et al., 2014). Bien que l'intensification ait contribué à développer la production des aliments à des prix plus bas, elle a néanmoins provoqué des problèmes en raison des impacts environnementaux, notamment le changement climatique, la déforestation, la dégradation des sols et l'altération des cycles globaux d'azote et de phosphore (Bouwman et al. 2009). Il existe un consensus sur le besoin de répondre à la demande de produits d'animaux à moindre impact environnemental (Godfray et al., 2012). Cela met l'accent sur la gestion des ressources renouvelables et non renouvelables, pour qu'on puisse garantir l'approvisionnement en quantités suffisantes de produits animaux-végétaux sans pour autant compromettre la capacité productive des agroécosystèmes à long terme (Dumont et al., 2014).

Dans ce volet de la thèse nous proposons un cadre analytique pour évaluation des systèmes d'élevage quant à leurs spécificités (composition des espèces, diversité des systèmes et pratiques alimentaires) ainsi qu'aux interactions entre les performances et impacts. Ce type de cadre vise à identifier le potentiel global d'amélioration des systèmes d'élevage et la marge de manœuvre pour augmenter les performances et aussi pour diminuer l'impact à l'environnement.

L'objectif de cette étude était d'identifier la différenciation spatiale, les compromis et synergies entre les indicateurs de performance et d'impact environnemental dans les territoires d'élevage en France. Nous avons formalisé le métabolisme territorial de l'azote, qui consistait à comptabiliser les flux d'azote des systèmes d'élevage, pour un total de 48 départements (une entité administrative française). Nous avons ensuite dérivé six indicateurs de performance et d'impact depuis l'inventaire des flux de façon à pourvoir identifier les différents types d'interactions, classées en synergies ou compromis. Notre analyse a eu pour but d'appréhender l'hétérogénéité des systèmes d'élevage. L'ensemble d'indicateurs représente l'efficacité des plantes et des animaux, l'approvisionnement en produits animaux et des impacts environnementaux d'après une perspective locale et autre mondiale.

Résultats et Discussion

L'hétérogénéité spatiale observée dans les zones d'élevage reflète les différents types d'interactions entre indicateurs de performance et d'impact. Ces interactions sont caractérisées par des synergies et des compromis, résultant de la diversité des systèmes d'élevage dans les territoires étudiés. La classification des interactions en synergie ou en compromis a permis dans un premier moment de comprendre la nature des interactions. Pour les synergies, plusieurs gains étaient possibles à la fois, comme pour des gains à la fois pour la production animale et l'efficience de conversion alimentaire, ainsi que de gains environnementaux avec la réduction des émissions de N2O. Pour ce qui concerne les compromis, lorsque des gains pour un indicateur se traduisaient par une perte pour un autre indicateur, on les a observés un antagonisme très important entre plusieurs indicateurs. Des hauts niveaux en conversion alimentaire étaient souvent contrastes à des bas niveaux d'autosuffisance et à des hauts niveaux de surplus azoté. Ensuite, la décomposition spatiale des interactions a révélé que dans des synergies les territoires pouvaient être classées dans des situations supérieures ou inférieures, tandis que pour le compromis la plupart des territoires étaient classés dans des situations d’antagonisme (haut niveau pour un indicateur et bas pour autre). Cette nature intrinsèque des compromis révèle des forts arbitrages entre les indicateurs de production et autosuffisance et surplus azoté. Cela signifie que, dans la plupart des cas, l'amélioration des indicateurs de performance (FCR et ASF) a été réalisée au détriment de l’environnement pour ce qui concerne les pollutions diffuses par des nitrates et d’une perte autosuffisance.

Cette nouvelle approche que nous avons proposée pour l’évaluation des performances et impacts dans les territoires d'élevage a apporté de nouvelles connaissances. Elle se base sur la sélection d’indicateurs issus d'une analyse des flux d’azote, suivi d’une caractérisation des types d'interactions et décomposition de l'hétérogénéité spatiale existante au niveau départemental. Notre analyse a révélé comment la configuration du secteur de l'élevage a influencé la performance territoriale dans l'utilisation des ressources et l'impact à l'environnement. Les caractéristiques de situations les plus désirables, en ce qui concerne les six indicateurs que nous avons étudiés, ont révélé le suivant : i) les régions favorisant une plus grande proportion de ruminants par rapport aux monogastriques, ii) la production laitière basée sur l’herbe. L'utilisation de la théorie de la viabilité (Aubin, 2009) pourrait permettre d'identifier espace de fonctionnement sécurisé dans les territoires d'élevage, en définissant l’ensemble des conditions idéales qui permettent aux systèmes de respecter les contraintes au cours du temps, et donc de se maintenir en bonne santé. Cela consisterait à naviguer dans les territoires d'élevage en jouant sur des leviers liés à i) la composition des espèces, ii) les taux de chargement et iii) les objectifs de production, afin de maintenir les territoires d'élevage dans des limites viables. Dans le cas de la Bretagne, cette théorie pourrait être utile pour équilibrer les pratiques des système d’élevage pour parvenir à des modes de production plus durables.

L'intensification de l'élevage a contribué à des bénéfices/avantages hétérogènes sur la fourniture des services culturels, socio-économiques et environnementaux

Des études récentes ont mis l'accent sur le rôle des agroécosystèmes dans la fourniture de multiples services écosystémiques. De par son impacte directe et indirecte sur l'utilisation du sol, l'élevage est un moteur majeur des services écosystémiques. Quoique quelques études portent sur la contribution d'élevage à la fourniture des multiples services, il reste toujours une lacune majeure dans les connaissances sur la fourniture de services à travers des territoires. Nous explorons l'hypothèse que l'actuel niveau de services culturels, socio-économiques et environnementaux dérivent des trajectoires d'intensification passées.

L'objectif de cette étude vise à comprendre le lien entre les changements des variables associés à l'élevage, l'utilisation du sol et caractéristiques socio-économiques sur l'actuelle fourniture de services culturels, socio-économiques et environnementaux. Nous exploitons l'avantage d'une base de données à long terme à l'échelle départementale avec des variables d'intensification, et aussi de données récentes basé sur les services culturels, socio-économiques et environnementaux. À l'aide d'une approche multivariée, nous avons étudiés simultanément les changements dans le procès d'intensification de l'élevage entre 1938 et 2010, et l'actuel niveau de fourniture de services. Notre analyse porte sur l'ensemble de 60 départements français où l'élevage joue un rôle majeur.

Notre étude a révélé que la fourniture des services était spatialement structurée et basée sur trois groupes de départements, caractérisés par différents niveaux de d'intensification. Chaque groupe était caractérisé par des taux variés des changements des variables d'intensification. Premièrement, le faible niveau de fourniture de services dans des zones de polyculture-élevage était associé à des changements autour de la moyenne nationale. Deuxièmement, des hauts niveaux de services environnementaux et culturels dans les territoires orientées vers les systèmes herbagers étaient particulièrement associés à un important changement dans la densité des herbivores (accrue de 95%) et des gains relatifs à la part des surfaces fourragères principales (accrue de 13%). Troisièmement, le haut niveau des services socio-économiques dans les territoires orientés vers l'intensification était principalement associé à des changements majeurs dans la densité des monogastriques (accrue de 1045%) et la productivité de lait (451%). Cette étude a fourni des connaissances pour comprendre les conséquences négatives sur les avantages que l'élevage fourni à la société. Des recommandations avisées sur l'intensification sont nécessaires en ce qui concerne la mitigation des émissions de GES d'origine anthropogénique.

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Ecole Doctorale ABIES

Título: Metabolismo sócio-ecológico das regiões de produção pecuária: uma abordagem de contabilidade ambiental

Palavras-chave: trajetórias de intensificação; metabolismo do nitrogênio; serviços ; produção pecuária

Resumo:

Durante o século XX, a produção pecuária na França passou por um desenvolvimento caracterizado por grandes mudanças, as quais hoje possuem frágil estabilidade. Pesquisas passadas sobre a sustentabilidade da produção pecuária focaram na performance econômico-ambiental, principalmente a nível animal e da fazenda. Poucos trabalhos abordaram os três pilares da sustentabilidade em escalas mais agregadas onde diferentes atividades pecuárias se combinam. Seria de grande utilidade uma abordagem que articule a produção pecuária, tanto de monogástricos como de ruminantes, ao uso da terra e de recursos a nível territorial. Esta tese de doutorado desenvolveu uma avaliação holística da produção pecuária no território metropolitano francês, mobilizando um conjunto de indicadores sobre as contribuições positivas e negativas do setor.

Foram constituídas três bases de dados para caracterizar a totalidade do território metropolitano francês a nível departamental. A primeira base de dados contém indicadores socioeconômicos, de uso da terra, e zootécnicos, no período de 1938-2010. A segunda base de dados fornece para o ano de 2010, indicadores de produção animal e vegetal. A terceira base compreende indicadores relacionados à contribuição da pecuária ao fornecimento de serviços culturais, socioeconômicos e ambientais. Com a primeira base nós modelizamos as trajetórias de intensificação da pecuária desde 1938 e identificamos os principais determinantes da dinâmica de mudanças ocorridas na produção pecuária. Com a segunda base, nós formalizamos o metabolismo territorial do nitrogênio, a partir do qual derivamos seis indicadores para avaliar a sustentabilidade da pecuária. Com a terceira base, nós estudamos o vínculo entre o atual nível de fornecimento de serviços e as trajetórias de intensificação.

Nossos resultados revelam uma diferenciação espacial da intensificação da pecuária desde 1938. Produtividade e densidade animal triplicaram nas regiões do Oeste, e aumentaram de 1.6 nas regiões Leste e do Massivo Central. Nas regiões com baixa produção pecuária, as áreas em pastagens recuaram de mais da metade, enquanto o tamanho médio das fazendas triplicou e a produtividade do trabalho quadruplicou. O metabolismo territorial revelou uma arbitragem entre autonomia proteica e produtividade animal. Impactos locais (excedente de nitrogênio/ ha) e globais (emissões N dos dejetos/ kg produto) caracterizaram uma arbitragem de difícil atenuação. A análise das contribuições positivas da pecuária mostrou que as regiões que seguiram trajetórias extensivas tenderam a fornecer maiores níveis de serviços sociais, culturais e ambientais; enquanto regiões que seguiram trajetórias mais intensivas tenderam a fornecer mais serviços socioeconômicos, ligados a empregos no setor.

A perspectiva histórica e a ampla cobertura espacial desta tese oferecem uma análise inédita da produção pecuária e da sua performance nas diferentes regiões. A tese gerou conhecimentos necessários à identificação de pontos estratégicos para melhorar a gestão da sustentabilidade visando o futuro da pecuária.

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Ecole Doctorale ABIES

Title : Socioecological metabolism of livestock areas: an environmental accounting approach

Keywords : livestock areas, intensification trajectories, nitrogen metabolism, services

Abstract : *The development of the livestock sector in the past century undergone a strong intensification. The current heterogeneity of livestock areas in France may have arisen from a spatial differentiation of intensification process. Different degrees of disconnection between livestock and land have resulted in contrasted levels of performance and impacts across areas. To date, a lot of research effort has been directed at measuring environmental impacts and economic performance of livestock systems at the farm level. Insufficient attention has been paid to the three dimensions of sustainability and to trade-offs among them. Existing livestock heterogeneities across areas also deserve more research. An approach that enables connecting livestock to land and resources, at regional level, could bring novel insights on the role of livestock in use and transformation of resources. The goal of this PhD was to develop a holistic assessment of livestock areas using multi-metric indicators encompassing positive and negative contributions.*

We compiled three databases at the department level: i) database 1 was related to socioeconomic, land use, and production characteristics of 88 French departments, within an extensive time frame (1938-2010); ii) database 2 included data on crop, fodder and livestock production for year 2010; iii) database 3 included measures of provision of cultural, environmental and social services for 60 departments. With the first database, we created a typology of intensification trajectories based on a multivariate approach. With the second database, we assessed the nitrogen metabolism of livestock areas, based on the material flows accounting (MFA) approach, from which we derived indicators of performance and impacts to study synergies and trade-offs. With the third database, we studied the influence of past intensification on the current provision of services by the livestock sector. A multivariate approach was used to assess how different rates of change in intensification variables determined contrasted levels of services.

First, we showed that the intensification of the French livestock sector was spatially differentiated and based on four trajectories, ranging from extensive to intensive livestock areas, and from crop specialized to areas where livestock had a small share of national production. Livestock productivity and stocking rates had a 3 fold increase in intensive areas, whereas extensive areas had a 1.6 fold increase. Crop specialized areas lose more than half of their original fodder area, and tripled the average farm size and more than quadrupled their labor productivity. Non-dominated livestock areas lose 30% of initial livestock population, and half of their initial fodder area. Second, the study of synergies and trade-offs revealed that gains in efficiency and economies of scale, often compromised other dimensions, e.g. through increased environmental impacts. The spatial analysis of relationship between performance and impacts revealed two types of synergies linked to the type of impact, either land or product-based. Both of which were in trade-off. Third, we showed that the provision of services was spatially structured and based on three types of service bundles, determined by different rates of change in intensification variables. Changes towards grazing systems resulted in higher provision of environmental and cultural services, whereas changes towards intensive systems resulted in higher levels of social services; but this was achieved at the cost of environmental services.

This PhD thesis furthered the understanding on the temporal trajectories of livestock sector across areas in France. This knowledge could help to improve livestock sustainability. Our work provided knowledge on the drivers that shaped current intensification patterns and the provision of cultural, environmental and social services. It could be used to examine options for desirable long-term changes of the livestock sector.

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Ecole Doctorale ABIES

Titre : Métabolisme socio-écologique des territoires d'élevage : une approche de comptabilité environnementale

Mots-clés : trajectoires d'intensification ; métabolisme de l'azote ; services ; production animale

Résumé :

Au cours du XXème siècle, l'élevage français a connu un formidable développement dont la poursuite se trouve actuellement fragilisé. L'effort de recherche sur la durabilité de l'élevage s'est focalisé sur la performance économique et environnementale, principalement au niveau de l'animal et de la ferme. Peu de travaux ont abordé les trois piliers de la durabilité à des échelles territoriales où les différentes filières animales se combinent. Une approche articulant l'élevage de ruminants et monogastriques à l'occupation du sol et à l'utilisation des ressources au niveau territorial fait actuellement défaut. Cette thèse développe une évaluation holistique de l'élevage dans les territoires métropolitains en mobilisant une batterie d'indicateurs abordant les contributions positives et négatives de l'élevage.

Pour l'ensemble du territoire métropolitain, nous avons constitué trois bases de données à l'échelle départementale. La première base contient des indicateurs socioéconomiques, d'occupation du sol, et de production animale sur la période 1938-2010. La seconde base fournit pour 2010 des indicateurs de production animale et végétale. La troisième base fournit des indicateurs mesurant la contribution de l'élevage à la fourniture de services culturels, socio-économiques et environnementaux. Avec la première base, nous avons modélisé les trajectoires d'intensification de l'élevage depuis 1938 et identifié les déterminants des dynamiques de changement de l'élevage. Avec la deuxième base, nous formalisé le métabolisme territorial de l'azote, duquel nous avons dérivés six indicateurs pour évaluer la durabilité de l'élevage. Avec la troisième base, nous avons modélisé le lien entre le niveau actuel de fourniture de services et les trajectoires d'intensification.

Nos résultats révèlent une différentiation territoriale de l'intensification de l'élevage depuis 1938. Productivité et densité animale ont triplé dans les territoires de l'Ouest, et augmenté de 1.6 dans les territoires de l'Est et du Massif Central. Dans les territoires sans élevage, la surface fourragère principale a reculé de plus de la moitié, tandis que la taille des fermes a triplé et la productivité du travail a quadruplé. Le métabolisme territorial révèle un arbitrage entre autonomie en azote et productivité animale. Les impacts locaux (surplus azoté / ha) et globaux (émissions excrétion azoté / kg de produit) forment un arbitrage difficile à atténuer. L'analyse des contributions positives de l'élevage montre que les territoires ayant suivi une trajectoire herbagère fournissent des services sociaux, environnementaux et culturels; alors que les territoires hébergeant les élevages les plus productifs fournissent surtout des services socio-économiques (emplois).

De par sa profondeur historique et sa couverture spatiale, cette thèse offre une analyse inédite de l'élevage et de ses performances dans les territoires. Elle apporte des connaissances pour identifier des leviers de durabilité pour l'élevage de demain.