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An Ecological Reading of Crop–Livestock Interactions—Gers, Southwestern France, 1950 to the Present

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Abstract: Mixed crop–livestock farming is usually considered to be beneficial for the environment, but the comprehensive characterisation of functional interactions between crops and livestock, and thus the assessment of their ecological relevance, remain problematic. In this article, we design a systemic reading grid focusing on the agricultural practices of crop–livestock interactions, which we organised in four groups according to the agronomic functions they fulfil and the ecological processes involved: (i) animals are used as a source of mechanical energy; (ii) rangelands and permanent grasslands, serving as a source of biomass to manage fertility, are spatially interwoven into the cultivated fields; (iii) on those cultivated fields, non-fodder crops are rotated/associated with fodder crops; (iv) the livestock consume locally produced fodder, grain and straw, and their excreta are spread on cultivated plots. Based on 86 interviews with retired and active farmers, we applied this grid to study the dynamics of crop–livestock integration in a small French agricultural region since 1950. We show that even though the number of mixed crop–livestock farms remains quite high, there has been a massive impoverishment of crop–livestock interactions within these farms. We discuss this trend and the contributions made by the reading grid.

Keywords: crop–livestock interactions; sustainable agriculture; farming systems; agroecosystems; history; comparative agriculture

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1. Introduction

Crop–livestock interactions are viewed as an important asset to improve the sustainability of agriculture [1,2]. Animal feed based on crops, crop residues or grassland grazing, as well as the spreading of animal excreta on cultivated plots, contribute to closing the carbon and nutrient cycles within agroecosystems [3–5] while limiting eutrophication [6] and the need for external inputs [7]. Similarly, the use of animal energy (animal traction) for certain crop operations [8–10] and the transportation of matter reduces the consumption of fossil fuels [11]. The inclusion of fodder crops in crop rotation [12] and grazing on certain cover crops [13] can contribute to reducing the pressure of weeds and crop pests. Finally, landscape mosaics that associate cultivated fields, grasslands and rangelands are less prone to erosion [14] and are home to a wider biodiversity than entirely cultivated areas [15]; this biodiversity contributes to regulating the effect of pests [16,17].

However, several studies carried out over the last decade conclude that the environmental performances of mixed crop–livestock farms are not superior than those of specialised farms [18–21]. This apparently surprising result can be explained by the definitions of mixed crop–livestock farms in these assessments [22,23]. Numerous works effectively use a "structural" definition that views mixed crop–livestock farming as the simultaneous presence of crops and animals on the same farm or territory, without prejudging the connections between the two types of activities [22]. This is, for example, the approach adopted by French agricultural statisticsnwhen defining "mixed crop-livestock" category. To be consideredthis class, crops and livestock must each contribute at least 33% of the farm's total standard gross production [24]. A farm could thus be classified as mixed crop–livestock although none of the above-mentioned interactions between crops and livestock are practiced on the farm [25]. Conversely, a farm where crops and livestock are closely interconnected but that only sells animal products will not be considered a mixed crop–livestock farm but a specialised farm [22].

A more "functional" approach to crop–livestock interactions is needed to grasp the specificities of these interactions, analyse their effects on ecosystems and, if the effects are indeed virtuous, assist in their development [23,25]. The first part of the definition provided by Séré et al. [26], often cited, represents a simple firstexample of taking these existing functional connections into account on mixed crop–livestock farms: "Livestock systems in which more than 10 percent of the dry matter fed to animals comes from crop by products, stubble or more than 10 percent of the total value of production comes from non-livestock farming activities" [26].

Some studies thus estimate the level of farm integration trough material flow intensity between livestock and crops [27–30]. In doing so, they do not consider the other roles that crop–livestock integration can play, such as regulating water flows, the effects of interactions between species, or those of cropping successions, as summarized by Moraine et al. [31]. A number of mixed crop–livestock farm typologies have been designed to account for the presence or absence of these various functions [31–36]. However, some of these typologies are fixed and do not allow a fine description of the variety of configurations [31–33,35]. Others studies provide disaggregated grids, making it possible to describe all hybrid situations [34,36]; however, the proposed categories do not each designate a homogeneous ecological phenomenon and therefore cannot be connected to a particular ecological or agronomic function.

In line with these works, the aim of this paper is to characterise, at the scale of a small region, the various forms mixed crop–livestock farming has taken at different times, between 1950 and the present day, and to link these forms of integration to a certain functioning of the cultivated ecosystem.

The region we studied, located in the Gers department in France, is a mixed crop–livestock area. The presence of monogastric animals and ruminants in this region, and the fact that we consider ancient historic periods, broadens the range of crop–livestock interactions studied, leaving room, for example, for draught animals. In order to compare the contrasting situations observed at different times and in different parts of the area, we found it useful to present our results using a simple grid, in which we distinguish four basic forms of crop–livestock integration. This comparative grid is also a result of this research, as we believe it could be used in others contexts. We then discuss both the dynamics of the evolution of crop–livestock interactions in this European region and the contributions made by this reading grid.

2. Materials and Methods

2.1. Study Area

The study area is located in the Aquitaine basin, in the South West of France. The centre of the Aquitaine basin specialises in grain cultivation, its surroundings in ruminant farming. According to statistical data, the intermediary zone shows a mixed grain and livestock trend, with bovines and monogastric animals [37] (Figure 1).

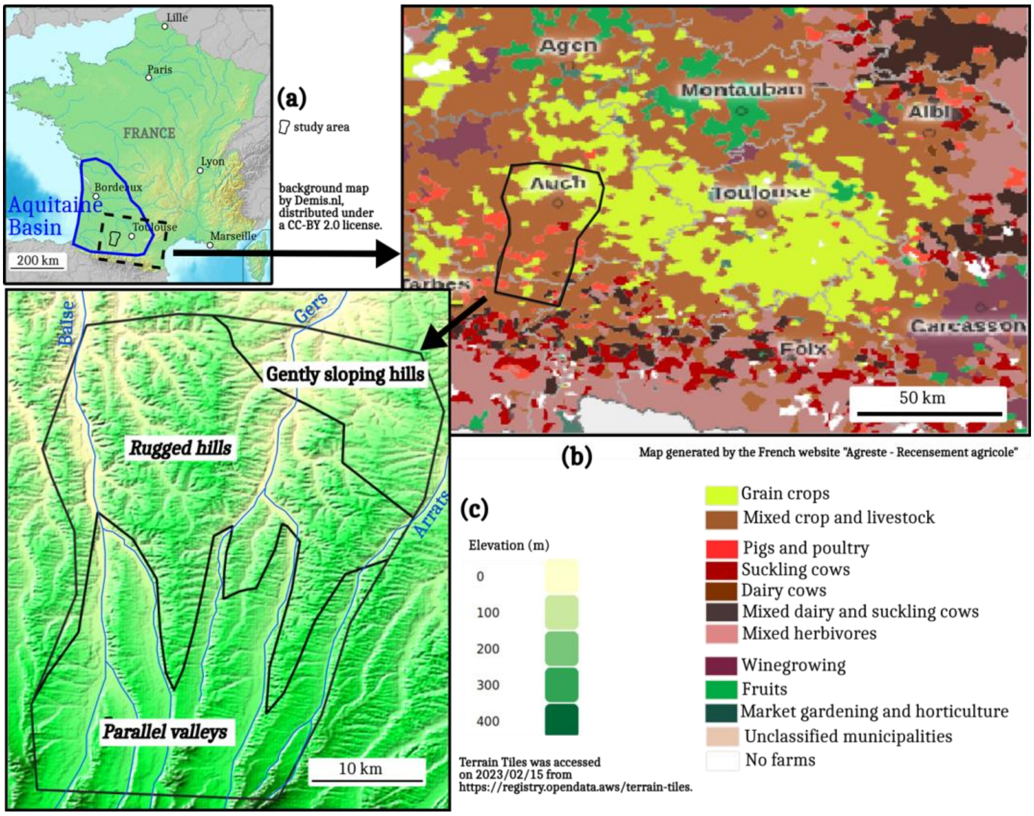

Figure 1. (**a**) Location of the study area. (**b**) Productive orientation of the municipalities in the southeast of the Aquitaine basin. (**c**) Geomorphological division of the study area.

The perimeter chosen for the study is a 50 km by 25 km strip that crosses this gradient, oriented south-north, that is home to about 1500 farms [37]. This strip runs all the way across the mixed crop-livestock region and extends 10 km into the grain region (Figure 1). This zone represents 20% of the surface of the Gers department, a department where 7% of farms specialise in cattle farming, 7% in monogastric animal farming and 14% are mixed farms [37].

The climate in the region is oceanic, with gentle winters and rainy springs. July and August, often prone to drought, are nonetheless outside the limits of the climatic water deficit [38].

Three pedoclimatic zones follow each other along a north-south axis (Figure 1). The south, upstream, is a series of parallel valleys, where the cultivated area is fairly flat (slopes of less than 15%) and covered with silty luvisols [39,40]. These valleys, close to the Pyrenean reliefs, receive an annual rainfall higher than in the north of the area (870 mm as compared to 685 mm, [38]). Further, they have been progressively developed for irrigation (pumping from rivers and canals) [39]. These two characteristics make it a region particularly suitable for summer crops (corn, soybean, sunflower).

Downstream, the north, with a drier climate and clay-rich calcareous soils, is divided into a southern rugged sector (slopes up to 50%) and a northern sector with gentle slopes (less than 25%) and deep soils, where the central grain plain of the south-eastern Aquitaine basin begins (Figure 1). Although handicapped by slopes, the rugged sector contains numerous sites suitable for building hillside irrigation reservoirs for rainwater, which were constructed during the 1970s and 80s [40].

The three zones, rugged hills and gently sloping hills in the north, and valleys in the south, all include downslopes and hydromorphic lowlands that cannot be cultivated unless they are artificially drained.

2.2. Fieldwork to Reconstruct the Production Systems of This Area since 1950

To study the history of crop–livestock interactions and their ecological role, we reconstructed the technical functioning of the main modes of agricultural production that have succeeded each other in the region since 1950.

To collect and analyse this data, we used the *agrarian diagnosis* method [41,42] which is part of the *comparative agriculture* conceptual framework [43,44]. Agrarian diagnosis is a standardised method designed to capture and explain farm diversity and change over time in a small agricultural region. Combining scales and disciplines—including agronomy, animal sciences and ecology—it is perfectly suited to a systemic and dynamic understanding of crop–livestock interactions at a micro-regional scale. This method makes it possible to consider in a relatively short period of time a very large number of variables, which are progressively prioritised as we gain a better understanding of local agriculture [41]. It is based mainly on field interviews and observations, and secondarily on statistical and bibliographical resources. The fieldwork was organized in three steps presented in the Figure 2: (1) landscape analysis, (2) historical investigation (3) characterisation of currents systems.

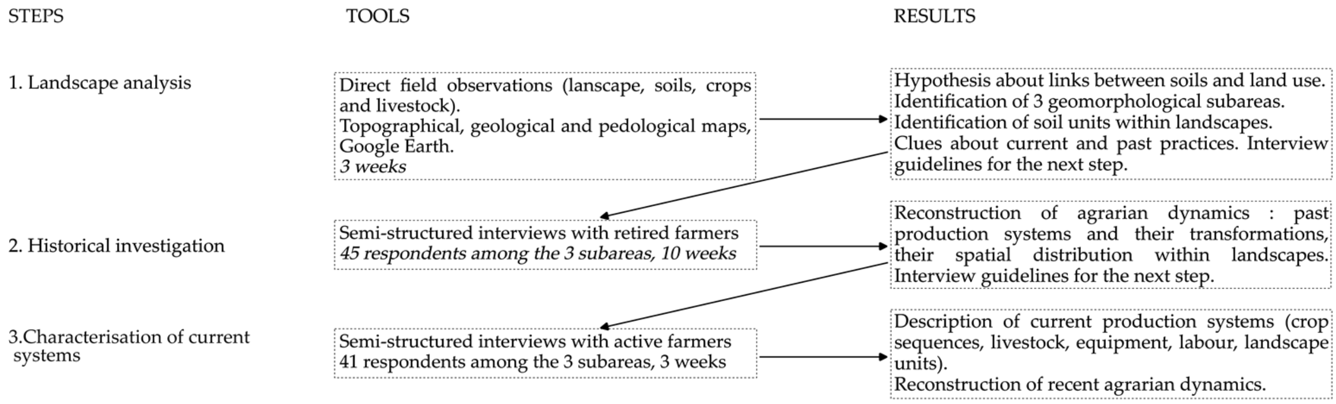

Figure 2. Data collection procedure.

Data were collected during a 4-month field study, between May and August 2020, by a single investigator.

Phase 1, the landscape analysis, lasted three weeks. The main variables considered were plot size, slope, exposure, soil depth, soil chemical and physical properties, hydromorphy, drainage and irrigation systems, climate, eco-landscape mosaic, livestock, crops and equipment, both through direct observations and bibliographic resources, mainly maps [39,40,45]. This first step served to formulate hypotheses about the constraints the environment exerts on agricultural activities, and about how the ecosystem is exploited. This was a necessary step in understanding the specific nature of crop–livestock interactions in this small region (for example, the use of manure on certain soil types to limit the summer water deficit for maize growing). At the end of this work, it was possible to distinguish the different soil units constituting the landscapes, as well as 3 large geographical entities dividing the study area (see Figure 1c), characterised by a homogeneity of landscapes and agricultural activities. This guided the investigations in the following phases.

In Phase 2, in a 10-week-long historical investigation, a total of 45 retired farmers aged 70–96 years were interviewed. The farms were selected to cover the diversity of environmental conditions identified during Phase 1. The interviews, semi-structured and lasting from one to three hours, aimed at reconstructing the history of farms and the functioning of the ecosystem they exploit, from the earliest years, sometimes as early as 1950, up to 2020 in the case of farms that had been passed on.

In Phase 3, 41 active farmers were interviewed in order to characterise current production systems. Farms were selected using the information collected during phase 2, in order to cover the diversity of environments, socio-economic conditions and agricultural productions existing in the area. The work carried out was similar to that of phase 2, but for the recent period (1990–2020).

The basic principle of the agrarian diagnosis method is the reduction of the diversity of farms reconstructed at different times into a limited number of ideotypic production modes, called *production systems*. Each production system is a model of the technical and economic functioning of a group of farms sharing similar production, surface area per worker, and equipment in similar environmental and socio-economic conditions.

A production system can be broken down into one or several *cropping systems* and *livestock farming systems*. A cropping system is a certain way of producing crops (succession of intra- and inter-annual crops, sequence of cropping operations following a specific calendar as well as specific tools and doses of inputs) [46]. A livestock farming system is a group of animals farmed in the same way (breeding, feeding, animal protection and use of products) [47]. Intersecting these two concepts, the *fodder system* is all the elements of the production system dedicated to the production of fodder [48].

Following these definitions, cropping and livestock farming systems hence designate not only production methods but also physical groups of livestock farmed in a similar manner and groups of plots cultivated in a similar manner. These groups of plots and livestock are organised in a specific spatial manner in relation to each other and are, or are not, connected by flows of matter, hydric flows and other ecological interactions. Cropping and livestock farming systems thus correspond to biophysical entities and can also be used to characterise crop–livestock interactions in ecological terms.

2.3. A Reading Grid of Crop–Livestock Interactions Based on Practices

Among the "functional" approaches to crop-livestock interactions, several formalisms exist in the literature. Several authors underscore the distinction between crop and livestock interactions that develop in space (e.g.: animals grazing on cultivated plots) and in time (e.g.: crop rotation between temporary grasslands and grain) [31,34,36]. While this distinction is relevant at a conceptual level, it does not qualify the nature of the ecological processes, but only the spatial and temporal organisation of the interacting elements, and we hence felt it was insufficiently operational to be retained as an interpretative criterion here. Among the approaches that look at crop-livestock agronomic interactions and their environmental effects, we can also distinguish those that focus solely on flows of matter [22] from those that include the other interactions that occur within the ecosystem [31,32,49]. This article is in the line of the latter, which give a more complete view of the ecology of crop-livestock interactions. For example, they look at the impact of grasslands included in crop rotation on the regulation of weeds and crop pests. Thus Schiere and Kater [32] consider five variables that make it possible to finely characterise the role of crop-livestock interactions in the functioning of agroecosystems (use of rangelands, draught animals, agronomic and anti-erosive role of grasslands, role of animal manure, role of crop residues). Their work nonetheless go beyond an agronomic and ecological characterisation of mixed crop-livestock farming, and the classifications they suggest include the interactions between crops and livestock through the use of capital, labour and inputs [33,50], which we will not look at here. Finally, a criterion often used to classify types of mixed crop-livestock farming is scale: several authors differentiate crop and livestock interactions within a farm from those between farms [35,49,51]. Although this differentiation is also conceptually relevant, it is not the scale of the interactions that defines their agronomic or ecological effects, and hence we did not retain it for our analysis.

The grid we designed thus focuses on the agronomic and ecological interactions between crops and livestock. It looks simultaneously at flows of matter and energy between livestock and crops and at the other effects on ecosystems provoked by these interactions, regardless of their scale within the small region. We distinguish four basic modes of crop-livestock interactions that can be combined in various ways: (i) animals are used as a source of mechanical energy (energy provision), e.g., providing draught power or grazing weeds;

(ii) an area of permanent grasslands or rangelands (the *saltus*), used as a source of biomass to manage fertility, is spatially interwoven into a cultivated area (*ager*) (fertility renewal, eco-landscape mosaic, water infiltration) [52]; (iii) on this *ager*, non-fodder crops are grown in combination with fodder crops (agronomic benefits of rotations and intercropping); (iv) the animals are fed with (and their bedding is made up of) local resources, and their excreta are spread on cultivated plots (closing the biomass cycle). The aim of this grid is to simply compare various situations, while providing a systemic representation of crop-livestock interactions in agronomic and environmental terms. The work presented in this article does not allow impacts to be quantified, but we refer to specific studies for each mode of crop-livestock interaction in the main results table.

3. Results

The evolution of production systems and the crop–livestock interactions that take place within them, developed in this section, are summarised in Figure 4.

3.1. 1950s: Livestock Farming Is the Cornerstone of Agronomic Logic

In 1950, the region was occupied by units of about five to about fifty hectares, consisting of family farms, sharecroppers, or large farms employing workers. These farms earned their income from the sale of grain and wine, productions that small and average farms supplemented by the sale of poultry, eggs and piglets. Despite considerable disparities in the production conditions, in terms of terrain, size of the farm and type of ownership, livestock and their fodder systems fulfilled a similar series of agronomic functions.

(i) Cattle were used as a source of mechanical energy for cultivation

Motorisation was very uncommon, and animal traction played a fundamental role at the time. Only farms larger than about 50 hectares, few of which actually existed, had tractors that they used, and only for a part of the work. On the other farms, cows and oxen of the local *Mirandaise* breed, harnessed in pairs, served for cultivation (ploughing, harrowing, rolling, weeding) and to transport manure, providing the energy required for all the harvests by pulling the grain reaper-binder, reaper, tedder, rake, carts, wagons, and tipcarts. There were few activities they were not involved in: in the fields, sowing, weeding around plants, spreading fertiliser and the corn harvest were carried out by hand; after the harvest, the corn cobs were shelled by hand, and from 1910 onwards the other grain was threshed by a static threshing machine activated by a steam powered engine or a tractor. This vast use of animal energy and human labour hugely limited the use of fossil fuels and hence greenhouse gas emissions.

(ii) A *saltus* used as a source of biomass to manage fertility was spatially interwoven into the *ager*

The majority of the fodder the draught cattle consumed was produced on areas reserved for livestock farming: permanent grasslands, moors and sparse woods that were grazed. These plant formations occupied the parts of the landscape the least suitable for crops. The grasslands were established on steep (over 30% gradient) slopes, with superficial soil, as well as in waterlogged lowlands with hypoxic soil conditions in winter and spring. The woods were abundant in the three zones, where they covered the steepest land (over 40% gradient). The moors covered some stony lands on the gentle slopes of the southern valleys.

Conversely, field crops (wheat, barley, oats, corn and legumes, as well as brown tobacco in the valleys) and vineyards were established on downslopes and hilltops.

The landscape was thus shared between two types of lands. On the one hand, the *ager* lands, regularly ploughed and sown, occupied the lower slopes and hilltops in the north and non-hydromorphic lands in the south. On the other hand, the *saltus* lands filled the remaining space and were divided between grazed and mowed-but-never-tilled grasslands and some only-grazed rangelands (woods and moors).

Although at the time they only offered a low potential for grain, the hydromorphic lowlands and mid and upper slopes turned out to be particularly suitable for grass production. The combination of these two types of surfaces made it possible to extend the grazing period, thus reducing the need for stored hay. The steepest hills could be grazed early on, at the end of winter and in the spring, and even earlier if they were well exposed. On the contrary, the lowlands, with deep soil, where water accumulated by gravity that could replenish the surface horizon through capillarity, provided grass until late into the summer. These lowland pastures were also the most productive, where farmers preferred to harvest hay.

These never-tilled grasslands on steep slopes and lowlands were made up of a spontaneous and varied herbaceous flora. The plant and animal biodiversity on these permanent grasslands, interwoven into the eco-landscape mosaic, likely contributed to regulating the number of crop pests. In addition, these grasslands, where the well-rooted grass cover encouraged infiltration, stored rainwater and reduced run-off at the scale of the catchment area. The hilltop grasslands thus prevented erosion on the tilled plots located further down, while also providing water through sub surface flows. The lowland grasslands, for their part, represented a temporary water storage area that sustained low water periods, as well as a buffer area that retained the colluvium extracted upstream. Hedges, mainly present within the network of damp lowland grasslands, enhanced the role of infiltration.

As well as optimising the agronomic potential of the various parts of the landscape, maintaining biodiversity and regulating water circulation, this combination of *ager* and *saltus* played a fundamental role in maintaining the fertility of cultivated soils.

The animals that grazed on the permanent grasslands, in the woods or on the moors in the daytime were sheltered in stables at night. Their dung was mixed there with straw, sometimes leaves and ferns taken from rangelands, and the manure produced was spread on the cultivated lands. In winter, all excrement was collected, because the animals, which were fed with hay collected mainly on the *saltus*, were kept in the stables all day long. Hence, the nutrients extracted from the *ager* soil every year, which the farm exported in the form of saleable products, could be renewed by those provided by organic matter drawn from the *saltus*. This spread manure was also a net contribution of organic carbon to the *ager* as, in addition to the straw harvested on the *ager*, it contained digested fibres from the rangeland and permanent grasslands and sometimes plant litter harvested on the rangelands. To a certain extent, this organic amendment could improve the "sticky" texture of clay soils and the crusting of loamy soils. And most of all, it maintained the clay-humus complex and hence the cation exchange capacity and water-holding capacity of the soils. The farms in the southern valleys, where corn cultivation was more important than in the north, thus protected this summer crop from drought by setting aside a large amount of their manure for this crop. The corn could be planted for three successive years on the same plot, so that it benefited from three cumulative applications of manure.

Finally, whether on cultivated land through manure spreading, or on the permanent grasslands thanks to the accumulation of root biomass, the combination of *ager* and *saltus* land enabled carbon sequestration, which limited greenhouse gas emissions.

Among the functions mentioned above, the role of manure from the *saltus* in the renewal of nutrients exported from the *ager* should be nuanced. Cereal crops received not only manure but also mineral fertilisers. The vines (which covered small areas) generally received only potassium and phosphorus mineral fertilisers, as manure was too rich in nitrogen.

(iii) Fodder crops were grown in association with non-fodder crops on the *ager*

Cultivated lands (*ager*) hence benefited from the presence of permanent grasslands and rangelands. However, these cultivated lands were also a space where fodder was produced, and it also played a fundamental agronomic role for non-fodder crops.

In fact, all cereal rotations included a legume fodder intended for distribution in the winter in the form of hay, along with the permanent grassland hay. These fodder crops were varied and most often planted for several successive years: 1 to 2 years for clover

(*Trifolium repens*) and birds-foot trefoil (*Lotus corniculatus*), 2 years for sainfoin (*Onobrychis viciifolia*), and 3 to 4 years for lucerne (*Medicago sativa*).

By fixing atmospheric nitrogen thanks to their root nodules, these fodder crops brought nitrogen into the soil. They also brought carbon, particularly through lucerne, the most widely cultivated fodder of all, with the longest implantation duration and deep roots.

Thanks to the deep roots and the long growth time, legume grasslands also reduced the loss of nutrients through run-off and encouraged their absorption. Like the permanent grasslands, they also contributed to rainwater infiltration at the scale of the landscape.

Lastly, these artificial grasslands competed with weeds for the duration of their implantation and consequently reduced the stock of weed seeds in the soil. In addition, lengthening the rotations, they limited fungal diseases and pest populations that attacked various crops.

(iv) The animals were fed with (and their bedding was made up of) local resources, and their dejections were spread on the cultivated plots

All the products from the *ager* intended for the livestock (legume fodder, straws, barley, oats and corn) were generally consumed on site, and the resulting manure was spread on cultivated land. Nutrient recycling from the *ager* to the *ager* was thus maximised.

Barley served to fatten cull cattle. Barley, oats and corn fed the farm's monogastric animals. While large farms could export oats and barley, the small and medium farms consumed everything they produced. This intra-consumption was motivated by a desire to make use of the labour present on the farm to increase the value of the harvests; recycling was therfore all the more intensive as the farms had little land. In the southern valleys in particular, the farms, which were smaller than in the north, raised more turkeys, raised sows to produce piglets and fattened more geese. Farms everywhere had laying hens. Poultry roamed around the farm in the daytime but were locked up at night, and their droppings could be collected. Pigs were raised indoors on straw and hence produced manure.

Hence, the recycling of the nutrients contained in products intended for livestock was generally optimised.

In short, in the 1950s, apart from soil preparation on large farms, manual cultivation practices, some mineral fertiliser and mechanised cereal threshing, almost all the essential agronomic activities were carried out by livestock that were integrated into the farm (Figure 3). This took place either directly through the cattle and monogastric animals or indirectly by the cattle fodder system. This use of crop–livestock interactions for their agronomic function also had beneficial environmental effects: maintaining biodiversity, regulating water flows and water quality, and limiting the use of mineral or greenhouse gas emissions (Table 1).

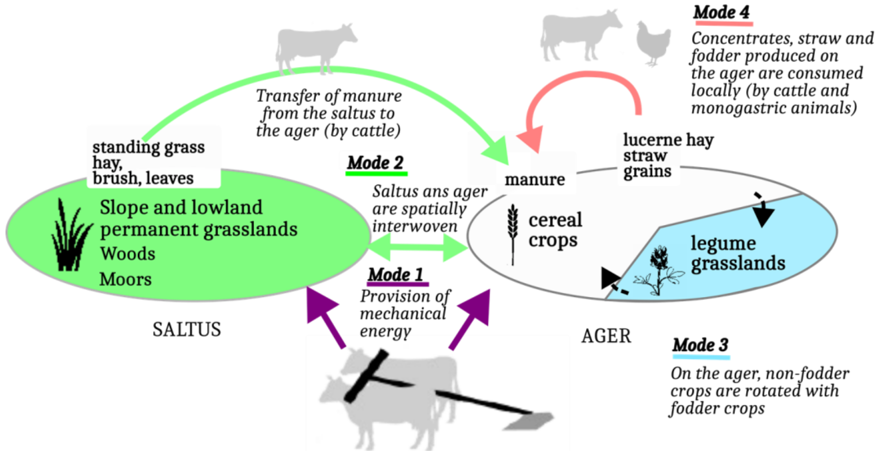

Figure 3. Crop–livestock modes of interaction that existed within farms in 1950.

Table 1. Modes of crop–livestock integration present in the 1950s production systems and the associated agronomic and environmental functions.

	Mode i:	**Mode ii:**	**Mode iii:**	**Mode iv:**
Mode of crop–livestock interaction	Animals are used as a source of mechanical energy (in cultivation practices as well as for transportation and product transformation).	A *saltus* (grasslands, rangelands, woodland) is spatially interwoven into the *ager* (tilled and sown plots) and provides biomass, generally in the form of manure.	Fodder crops are grown on the ager, in rotation or intercropped with non-fodder crops.	Local recycling of the biomass intended for animal consumption:(i) the animals are fed (and their bedding is made up of) local resources, and their excreta are spread on cultivated plots ;(ii) reciprocally, crops intended for animal fodder are consumed on the farm or in the region.
Agronomic and environmental functions	- low consumption of fossil fuels and hence little CO_2 directly emitted by cultivation and harvesting practices	- complementary usage of different parts of the landscape and maximisation of ruminant grazing periods - mosaic landscape with both croplands and semi-natural habitats enhancing biodiversity (a) and thereby pest regulation (b) - infiltration of water in the catchment area due to the perennial nature of these plant formations and substantial reduction in erosion (c) - carbon sequestration in grasslands (d) - renewal of *ager* fertility through biomass transfer rather than mineral fertilisers (e) - increase in the level of organic matter in the *ager* soils (agronomic and hydrological role) through manure spreading (f)	- renewal of nitrogen fertility by forage legumes (a) - temporary grassland within the landscape mosaic increases water infiltration, thus limiting erosion (b) - when destroyed, fodder crops leave behind a higher organic matter content (c), which increases water holding capacity (d) and water infiltration (e) - fodder covers and crops retain nutrients that would otherwise be lost through run-off and leaching, saving nutrients and reducing eutrophication (f) - specific biodiversity and eco-landscape mosaic (g) - weed regulation (h)	- recycles nutrients and biomass, reduces the use of mineral fertilisers (a), makes it impossible to have a concentration of livestock farms in regions where feed is imported, and prevents water eutrophication due to over abundant dejections (b)

Table 1. *Cont.*

Examples of studies quantifying these environmental processes in other locations	Spugnoli and Dainelli., 2013 [53]	(a) Fahrig, 2003 [54], Duflot et al., 2017 [55], Tscharntke et al., 2005 [56] (b) Gardiner et al., 2009 [57] (c) Burkart and James, 2005 [58], Brazier et al, 2007 [59] (d) Schuman et al., 2002 [60] (e) Powell et al., 1996 [61], Achard et Baroin, 2003 [62], Diarisso et al., 2015 [63] (f) Khaleel et al., 1981 [64]	(a) Rasmussen et al., 2012 [65] (b) Hendrickson, 1963 [66], Sun et al., 2022 [67] (c) Schulz et al., 2014, [68] Rubio et al., 2021 [69], Johnston et al., 2017 [70] (d) Libohova et al., 2018 [71] (e) Boyle et al., 1989 [72] (f) Garnier et al., 2016 [73], Lantinga et al, 2013 [74], Randall et al., 1997 [75] (g) Duflot et al. 2015, [55], Hoeffner et al., 2021 [76] (h) Liebman and Dyck, 1993 [77] For a general synthesis, refer to Martin et al., 2020. [78]	(a) Akram et al., 2019 [79], Burkart and James, 2005 [58] (b) van der Werf et al., 2005 [80], Mallin and Cahoon, 2003 [81], Tamminga, 2003 [82]

3.2. The 1960s: The Tractor Replaces Animal Energy and Specialisation Emerges

From 1955 onwards, new motorisation methods, mineral fertilisers and chemical control were progressively adopted, reducing the auxiliary role played by livestock systems.

Henceforth, production systems were clearly differentiated into four productive orientations, one specialising in crops and the others representing three distinct combinations of crop–livestock integration (see Figure 4).

Many of the large farms (over 50 ha) completely abandoned cattle farming from 1960 onwards. Those that had the most land and capital specialised in grain crops (mainly wheat and barley at the time) by extending the *ager* to cover the whole farm. This conversion of sloping and lowland grasslands into cereal fields involved vast drainage works, the removal of hedges and investment in powerful tractors.

The slightly smaller farms, which also had capital, followed the same path but supplemented grain cultivation with monogastric animal farming in buildings (poultry, laying hens, sows, pig fattening, battery-farmed calves). These monogastric animals were generally fed with grain produced on site, and their manure slurry was spread on the farm (mode iv: crop–livestock integration).

On the contrary, small and medium farms with a low investment capacity maintained multiple crop and livestock production as well as the organisation of work and cultivated space of the previous period. The tractor did away with the traction role cattle played, but the herd was kept and adapted to suckled calf production by crossing with beef breeds, then by adopting the *Blonde d'Aquitaine* breed. It was even extended thanks to motorised hay harvesting tools.

Pursuing a movement that had already begun during the earlier period, a few farms that had lowlands completely shifted their herds to milk production. In many cases, they continued to produce grain for sale alongside the livestock farming. While monogastric livestock activity was often eliminated on dairy farms, the dairy cows consumed grain produced on the farm; thus, internal recycling similar to the previous biomass recycling took place (mode iv).

Overall, in both suckler and dairy farming, the only major modification of the fodder systems was mechanisation, and hence *saltus*–*ager* interactions (mode ii), fodder–non-fodder rotations (mode iii) and biomass recycling (mode iv) were maintained at the same level as in the former period.

3.3. 1975 to 1995: Intensification of Fodder Cultivation and Irrigation Transform Crop–Livestock Integration

During the 1970s and 1980s, crop–livestock interactions on farms that had kept their cattle were completely transformed by the massive spread of irrigation infrastructure for the purpose of developing corn cultivation, as well as by the intensification of fodder systems.

In the valleys to the south, canals and then underground pipelines carried water from rivers to progressively serve the majority of plots. On slopes, in the north from 1970–1975 onwards, when topographical conditions permitted, individual or collective hill reservoirs were set up.

Lowlands, earlier occupied by permanent grasslands, were those with the highest potential for irrigated corn cultivation due to their soil depth and the organic matter accumulated under the grassy cover. To optimise the use of the irrigation water and the infrastructure created, the land was drained to be converted into cornfields. Until this time, these lands had been the main source of cattle fodder; however, as this activity was less profitable than corn cultivation, cattle farming was often terminated to be replaced by indoor pig farming, poultry or battery-farmed calves, which could not compete in terms of land use. As a result, in these new production systems, interactions based on the complementarity of the *ager*–*saltus* and fodder–non-fodder crops (modes ii and iii) disappeared, leading in the shorter and longer term to a reduction in soil fertility. Mode iv was maintained, although in an attenuated manner: while the indoor farming animals ate grain produced on the farm, and although their dejections were still spread on the farmland in the form of manure slurry, the protein content of their feed was now provided by imported soybean.

Farms that raised cattle remained as the majority. However, crop–livestock integration also decreased on these farms. Suckler and dairy farms saw large investments, which simultaneously reinforced the economic role of cattle and weakened the ecological functions their fodder system played.

Thus, on these farms, the permanent lowland grasslands were progressively drained between 1970 and 1990 to be merged with the *ager* (mode ii). To replace these former permanent lowland grasslands, ryegrass was now added to the grain and leguminous forage rotation, as a one-year crop or as catch crop before a summer crop (mode iii). Thanks to soil preparation, sowing, abundant mineral fertilisers, and investment in silage equipment, these temporary ryegrass grasslands provided far higher dry matter yields, making it possible to feed more cattle per surface unit. Sloping grasslands, which were difficult to mechanise, were not affected by this extension of the *ager*.

As crops were progressively extended down to the stream or river, and the land around these watercourses was drained, the hydrological buffer role these former low-lying grasslands played, along with the wet grassland ecosystems and their hydrophilic species, disappeared. Lastly, the *saltus*–*ager* fertility transfer that had in any event become obsolete due to the low cost of mineral fertilisers, was drastically reduced by this contraction of the *saltus*. Henceforth, this transfer only took place during the harvesting of hay on sloping grasslands.

Farms with dairy cows often specialised in this production. Cereal acreage shrank to a level just sufficient to feed the dairy herd, with high energy concentrates (barley and grain corn) - mode iv -, as straw for bedding could be harvested for free on neighbouring grain farmers' lan. However, no manure was returned to the grain farmers' plots (mode iv). Moreover, in comparison to the earlier period, the level of autonomy the dairy farms enjoyed in terms of protein matter decreased, because imported soybean cakes were included in the rations. The nature of the forage areas varied from farm to farm: permanent grasslands if the land was rugged, corn silage if the farm had lowlands or irrigation and, systematically, temporary ryegrass grasslands.

A minority of the suckled calf farms, located on sloping lands unsuitable for crops, also began to specialise and became grass farms with permanent grassland fields on slopes and lowlands (mode ii) and temporary grasslands in rotation with a few grain crops on arable land (mode iii), ensuring an autonomy in concentrates but not in straw (mode iv).

Most of the suckled calf farms nonetheless remained mixed crop–livestock farms. Grain crop farming, focusing on sales, satisfied the cattle's concentrate requirements and moreover, the needs in terms of straw. Cattle farming focused on the production of 6- to 8-month calves that were fattened in Italy or Spain. Monogastric animal farming continued but was limited only to goose and duck fattening. Geese and ducks were bought from a stock breeding farm and force-fed for about 20 days, with corn grain produced on the farm or bought in the region. With the drop in monogastric animal and light calf farming, these farms consumed less and less of the concentrates they produced (mode iv).

3.4. 1990–2010: Decline in Cattle Farming

After three decades favourable to cattle production, the number of mixed crop–livestock systems with suckled calf and dairy farming fell drastically after 1990, to the benefit of grain farm systems that can include an indoor livestock farming activity. Since then, the tillable land in the territory that had been completely drained by around 1995 has been almost entirely devoted to the production of cereals and oil as well as protein-rich crops.

Cattle farming only subsists on farms with land that is too steep (over 30%) to be worked, mainly in the form of suckling cows. The herd size has been adjusted to the extent of the steeply sloping land. Farms prefer to dedicate their less sloping land to grain crops. Fodder crops are nonetheless sown on this land in order to constitute stocks for winter and summer, as the permanent sloping grasslands are difficult to harvest with the wider machinery that farms now use. Consequently, there is a fodder–non-fodder crop rotation (mode iii), but it now only involves a part of the tillable land. In addition, when the permanent sloping grasslands are not harvested, and cattle are not stabled in shelters for the night, the *saltus–ager* fertility transfer (mode ii) no longer takes place. Finally, the 1990s and 2000s saw the end of complementary duck force-feeding farming within mixed crop cattle farms (mode iv).

3.5. Since 2010: Development of Organic Agriculture with No Real Crop–Livestock Reintegration

Between 2010 and 2021, organic agriculture carved out a significant space in the region (5% of the total cultivated areas of the department in 2010, 26% in 2021 [83,84]).

The only commercial fertilisers permitted in organic farming (industrial organic waste, poultry droppings) are expensive. Under these conditions, organic grain farmers, most of whom have no livestock to produce manure, opt for a reduced fertilisation.

Legumes (mainly soybean, as well as lentils, chickpeas, horse beans) that do not require nitrogen fertilisation are hence more present in organic crop rotations than non-leguminous crops. When water resources permit, soybean, a summer crop that consumes vast amounts of water but is lucrative, occupies up to two-thirds of the total cultivated area.

The basal fertilisation for these leguminous crops and complete fertilisation for other crops (straw grains, corn, flaxseeds, sunflower) are either not applied or provided by purchasing industrial organic fertilisers or by slurry and manure, usually from monogastric livestock farms in the region. The use of these other farm effluents clearly represents a crop–livestock interaction (mode iv). However, the conventional farmers who give away this manure previously spread it on their own land; they now replace it by purchasing an equivalent quantity of fertiliser units in the form of mineral fertiliser. All in all, while organic grain farming clearly relies on local animal manure, this fertilisation is no more than the reallocation of a resource previously used by conventional farming. This does not therefore change the level of recycling of animal dejections in the region.

Some organic farmers incorporate a lucerne or clover crop in their rotations (mode iii). However this occurs only in two situations: (i) on sloping plots with low potential, very rarely on deep soil downslopes in a valley, and even less on irrigable land; (ii) the first three years following the conversion, before a farmer can obtain certification, during which the sale price without certification does not cover the production cost for grain crops.

In other situations, however, farmers generally dispense with the agronomic role of fodder crops included in the rotations. Weeds can be destroyed mechanically, by hoeing or harrowing or by using a false seedbed. An extension of rotations to 5 or 7 years serves to control pests and diseases.

The lucerne and clover that organic grain farmers grow are generally harvested by neighbouring farmers who still rear livestock (mode iv). However, they cannot absorb all the supply: the region has become an exporter of legume hay, destined for the Massif Central or dehydration channels.

Thus, although by banning synthetic inputs the conditions of production of organic agriculture are similar to those of the 1950s, organic farmers in the 2020s are far less dependent on livestock farming systems than their predecessors of the 1950s for fertilising crops and managing pests and weeds. This new mode of grain cultivation, with a low level of chemical inputs, has therefore only slightly raised the level of crop–livestock integration in this region over the last decade. The number of heads of cattle in the department decreased by 28% over the same period [37].

Two improvements, however, can be noted. They concern biomass cycles involving livestock (mode iv). (i) Even if not well developed, since 2010 more and more grain farmers have been asking for manure in exchange for the straw or standing fodder they provide. (ii) An increasing share of suckler farmers are fattening their calves up to 12 months rather than selling them lean at 6 months. This increases the proportion of farm-produced grain consumed by the livestock farming system.

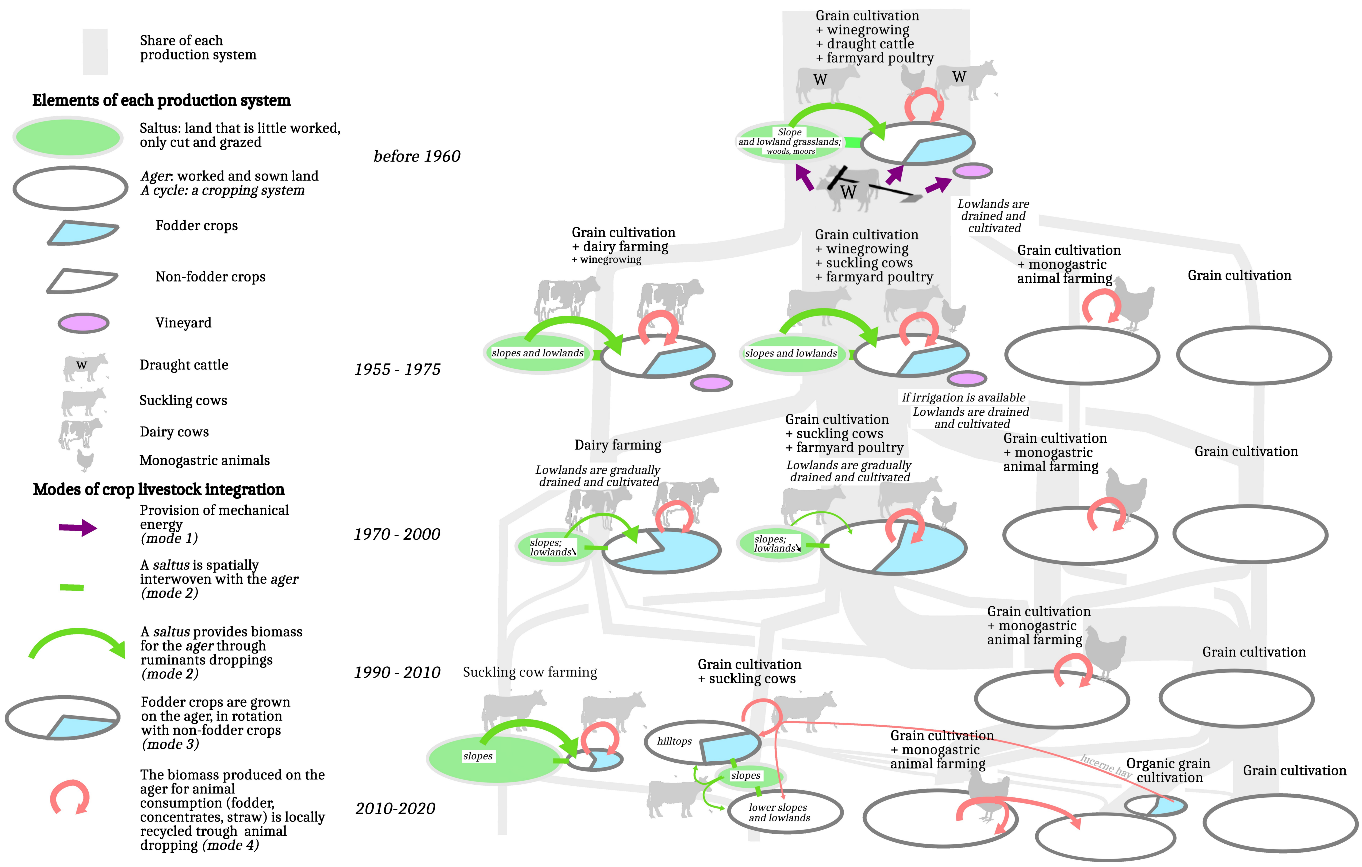

Figure 4. Nature and intensity of crop–livestock interactions implemented within current and past production systems in the study area.

4. Discussion

4.1. Crop–Livestock Disintegration Operates at Two Levels

This article shows that the decline of mixed crop-livestock farming in the Gers has two components. The first is linked to specialisation, with a growing share of farms specialising in irrigated or rainfed crop production—used at least partly to feed animals reared elsewhere – and a reduction in animal numbers, especially from 1990s onwards as far as cattle is concerned. This form of disintegration between crop and livestock is well documented in the literature for numerous other regions [3,85,86] as well as at a global scale [35]. From the second half of the 20th century onwards, especially in industrialised countries, the mechanisation of agricultural operations, the development of chemistry and the possibility of transporting matter over long distances (particularly for animal feed) encouraged farms and regions to specialise in one or the other of these activities. In France, according to the latest agricultural censuses, livestock farming continues to decline (28% reduction in the number of farms with livestock between 2010 and 2020 as compared to only 3% for grain crops and 20% for all French farms [37]) and it tends to disappear in some regions specializing in crops, like the Parisian basin or the north of the country.

What this study also shows is that the weakening links between crops and livestock goes beyond farm specialisation. In the region studied, mixed crop-livestock farming remains the main orientation in the majority of communes in 2020 according to agricultural statistics [37] (Figure 1b). Yet, as we saw, the role of livestock farming, and its interactions with crop cultivation, has seriously declined since the 1950s: animal energy is no longer used; the *saltus* and the agronomic functions it provided, particularly for the fertility of cultivated land thanks to the transfer of matter via ruminants, has been reduced to some slopes, mostly grazed, and of which only the least sloping are still mowed; crop rotation between grasslands and grain, and the associated agronomic benefits, now only exist on a part of the land on farms where cattle are present, and in a transitory manner, or on land that is difficult to cultivate on organic farms; the decline of the overall herd automatically reduces the permanent and rotated fodder area; the recycling of nutrients and biomass through animal feed (and straw bedding in indoor spaces) using locally cultivated resources, and the spreading of slurry or manure on cultivated plots persists but with the import of mineral fertilisers for crops and feed for animals (with a high protein content in particular) the cycles are now mainly open. Thus, although livestock farming and crop cultivation still coexist in the region, and on a majority of farms, the integration of these activities has gradually become a juxtaposition and the agroecological functions have been degraded. The low environmental performance of crop-livestock farming highlighted by certain studies [18–21] finds a potential explanation here and the perspectives for agroecological transition, thus set within a historical dynamic, become more concrete.

This more functional and comprehensive approach to mixed farming is present in the literature [31,32,49] but its use here to account for the historical dynamics of crop-livestock disintegration is novel.

4.2. Relevance of a Systemic Grid and Perspectives for Future Research

The grid developed in this article can be used to account for changes in crop-livestock interactions over time and to compare production systems that integrate crops and livestock in different ways at a given period. Compared to approaches focusing on matter flows [22,27,28,30,87] the grid we suggest present the interest of considering other functions at play within ecosystems, such as regulation of hydrology or pest pressure through lowland permanent grasslands and hedges. However, unlike the NiCC'El tool developed by Martel el al. [22,30], in its current form our grid does not allow us to measure a degree of interaction based on statistical data, and this could be a useful path to explore in the future

Compared to other reading grids that take into account both material flows and other ecosystem functions [31,34–36] this one brings together two properties at once.

(i) It doesn't seem to us to miss any important functions while limiting itself to four categories. In particular, it takes into account the role of the *saltus* in interaction with the *ager*, whose importance for the agroecological transition in Europe has recently been highlighted by Poux and Aubert [88]. Using of this grid in other situations would make it possible to test its genericity and improve it. Situations where animal grazing on cultivated plots plays a role in managing weeds [9] or pests [8] or where a partially forested *saltus* interacts with the *ager* via livestock farming to create a complex landscape mosaic [2] would be particularly interesting to study. Similarly, analysing the types of agriculture where animal feed is largely based on crop residues like straws [89] would enrich the representation of carbon and nutrient recycling on cultivated land via livestock farming proposed in this grid (mode iv).

(ii) Above all, the categories of this grid are homogeneous from the point of view of the pair of interacting objects and the way they interact. This is what makes this grid systemic: each of these interaction categories corresponds as much to a certain set of effects on the ecosystem as to a certain technical operation of the farm. Studies carried out on some ecological processes at finer scales (e.g., those cited in Table 1) can thus be resituated in the more global functioning of the farm.

Further studies are required to identify the causes of trends highlighted using this grid: decline in crop-livestock integration the associated agroecological functions. Garrett et al., [35], e.g., identified generic factors. Low farm prices relative to wages, low input costs, and subsidies favour the separation of crop and livestock systems. Cultural considerations, specific soil and climate conditions and protectionist policies work in the opposite direction. Other authors [20,90–92] also emphasise the role of prices, subsidies and collective action. Such an analysis of the factors is linked to the one developed here at the agroecological level and is essential, not only to identify the types of crop-livestock interactions that are beneficial from an environmental viewpoint, but also to accompany their reintroduction. Research-action studies [93] possibly accompanied by models [58], could then be conducted.

5. Conclusions

Based on the agronomic functions and ecological processes of crop–livestock associations in farming systems, the grid proposed in this article allows adaptation of the geographical scale of analysis and consideration of a greater historical depth. The scale of analysis should include a territory wider than the farm area. Uncultivated land outside the farm can play a key role, as this type of land was formerly the case in the region presented here. Furthermore, it is fundamental to take time into account. The functions assigned with livestock can evolve over time. In Gers, livestock was primarily a production tool: a source of energy and manure and the usual means to control weeds. Hence, each farm had to have animals. These animals were a functional complement to crops in truly agroecological farming systems. Gradually, this role has been lost. While they are still present in farms, the animals are simply a source of production. Crops are, at least partly, used for livestock. But even in this case, inputs are used, and farming systems are no longer agroecological. This case study also underlines that these transformations in the relationship between crops and livestock do not affect all farms in the same way, even in a small region like Gers. Thanks to its systemic nature, the grid proposed in this article allows us to grasp this polymorphic character of crop–livestock interactions, which changes from era to era and from one farm to another. Finally, it helps to prevent unfounded conclusions on the environmental benefits of crop–livestock associations.

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References

1. Franzluebbers, A.; Martin, G. Farming with Forages Can Reconnect Crop and Livestock Operations to Enhance Circularity and Foster Ecosystem Services. *Grass Forage Sci.* **2022**, *77*, 270–281. [CrossRef]
2. Lemaire, G.; Franzluebbers, A.; Carvalho, P.C.F.; Dedieu, B. Integrated Crop–Livestock Systems: Strategies to Achieve Synergy between Agricultural Production and Environmental Quality. *Agric. Ecosyst. Environ.* **2014**, *190*, 4–8. [CrossRef]
3. Peyraud, J.-L.; Taboada, M.; Delaby, L. Integrated Crop and Livestock Systems in Western Europe and South America: A Review. *Eur. J. Agron.* **2014**, *57*, 31–42. [CrossRef]
4. Thorne, P.J.; Tanner, J.C. Livestock and Nutrient Cycling in Crop–Animal Systems in Asia. *Agric. Syst.* **2002**, *71*, 111–126. [CrossRef]
5. Fanjaniaina, M.L.; Stark, F.; Ramarovahoaka, N.P.; Rakotoharinaivo, J.F.; Rafolisy, T.; Salgado, P.; Becquer, T. Nutrient Flows and Balances in Mixed Farming Systems in Madagascar. *Sustainability* **2022**, *14*, 984. [CrossRef]
6. McIsaac, G.F.; David, M.B.; Gertner, G.Z.; Goolsby, D.A. Nitrate Flux in the Mississippi River. *Nature* **2001**, *414*, 166–167. [CrossRef]
7. Allen, V.G.; Baker, M.T.; Segarra, E.; Brown, C.P. Integrated Irrigated Crop–Livestock Systems in Dry Climates. *Agron. J.* **2007**, *99*, 346–360. [CrossRef]
8. Pernollet, C.A.; Simpson, D.; Gauthier-Clerc, M.; Guillemain, M. Rice and Duck, a Good Combination? Identifying the Incentives and Triggers for Joint Rice Farming and Wild Duck Conservation. *Agric. Ecosyst. Environ.* **2015**, *214*, 118–132. [CrossRef]
9. Popay, I.; Field, R. Grazing Animals as Weed Control Agents. *Weed Technol.* **1996**, *10*, 217–231. [CrossRef]
10. Starkey, P.H.; Ndiame, F. Animal Power in Farming Systems. In *Proceedings of Networkshop Held*; GTZ: Eschborn, Germany, 1986; pp. 17–26.
11. Dikshit, A.K.; Birthal, P.S. Environmental Value of Draught Animals: Saving of Fossil-Fuel and Prevention of Greenhouse Gas Emission. *Agric. Econ. Res. Rev. Agric. Econ. Res. Rev.* **2010**, *23*, 227–232. [CrossRef]
12. Robson, M.C.; Fowler, S.M.; Lampkin, N.H.; Leifert, C.; Leitch, M.; Robinson, D.; Watson, C.A.; Litterick, A.M. The Agronomic and Economic Potential of Break Crops for Ley/Arable Rotations in Temperate Organic Agriculture. *Adv. Agron.* **2002**, *77*, 369–427.
13. Schuster, M.Z.; Harrison, S.K.; de Moraes, A.; Sulc, R.M.; Carvalho, P.C.F.; Lang, C.R.; Anghinoni, I.; Lustosa, S.B.C.; Gastal, F. Effects of Crop Rotation and Sheep Grazing Management on the Seedbank and Emerged Weed Flora under a No-Tillage Integrated Crop-Livestock System. *J. Agric. Sci.* **2018**, *156*, 810–820. [CrossRef]
14. Rodríguez-Blanco, M.L.; Taboada-Castro, M.M.; Taboada-Castro, M.T. Linking the Field to the Stream: Soil Erosion and Sediment Yield in a Rural Catchment, NW Spain. *CATENA* **2013**, *102*, 74–81. [CrossRef]
15. Benton, T.G.; Vickery, J.A.; Wilson, J.D. Farmland Biodiversity: Is Habitat Heterogeneity the Key? *Trends Ecol. Evol.* **2003**, *18*, 182–188. [CrossRef]
16. Toivonen, M.; Huusela-Veistola, E.; Herzon, I. Perennial Fallow Strips Support Biological Pest Control in Spring Cereal in Northern Europe. *Biol. Control* **2018**, *121*, 109–118. [CrossRef]
17. Tschumi, M.; Albrecht, M.; Entling, M.H.; Jacot, K. High Effectiveness of Tailored Flower Strips in Reducing Pests and Crop Plant Damage. *Proc. R. Soc. B.* **2015**, *282*, 20151369. [CrossRef]
18. Minviel, J.J.; Veysset, P. Are There Economies of Inputs in Mixed Crop-Livestock Farming Systems? A Cross-Frontier Approach Applied to French Dairy-Grain Farms. *Appl. Econ.* **2021**, *53*, 2275–2291. [CrossRef]
19. Perrot, C.; Dominique, C.; Helene, C. Économies d'échelle et économies de gamme en production laitière. Analyse technico-économique et environnementale des exploitations de polyculture-élevage françaises. *Rencontres Autour Des Rech. Sur Les Rumin.* **2012**, *4*, 33–36.

20. Ryschawy, J. Eclairer les Conditions de Maintien D'exploitations de Polyculture-Élevage Durables en Zone Défavorisée Simple Européenne. Une Étude de cas Dans les Coteaux de Gascogne. Ph.D. Thesis, Université de Toulouse, Toulouse, France, 2012; p. 211.
21. Veysset, P.; Lherm, M.; Bébin, D.; Roulenc, M. Mixed Crop–Livestock Farming Systems: A Sustainable Way to Produce Beef? Commercial Farms Results, Questions and Perspectives. *Animal* **2014**, *8*, 1218–1228. [CrossRef]
22. Martel, G.; Dieulot, R.; Durant, D.; Guilbert, C.; Mischler, P.; Veysset, P. Mieux coupler cultures et élevage dans les exploitations d'herbivores conventionnelles et biologiques: Une voie d'amélioration de leur durabilité? *Fourrages* **2017**, *13*, 235–245.
23. Mischler, P.; Tresch, P.; Jousseins, C.; Chambaut, H.; Durant, D.; Veysset, P.P.; Martin, G.; Fiorelli, J.-L.J.-L.; Chedly, H.B.; Pierret, P. Savoir Caractériser Les Complémentarités Entre Cultures et Élevage Pour Accompagner La Reconception Des Systèmes de Polyculture-Élevage Dans Leurs Transitions Agroécologiques. *Renc. Rech. Ruminants* **2018**, *24*, 11–20.
24. European Commission. Commission Regulation (EC) No 1242/2008 of 8 December 2008 Establishing a Community Typology for Agricultural Holdings. *Off. J. Eur. Union* **2008**, *335*, 226–247.
25. Ryschawy, J.; Joannon, A.; Gibon, A. Mixed crop-livestock farm: Definitions and research issues. A review. *Cah. Agric.* **2014**, *23*, 346–356. [CrossRef]
26. Seré, C.; Steinfeld, H.; Groenewold, J. *World Livestock Production Systems*; Food and Agriculture Organization of the United Nations: Rome, Italy, 1996.
27. Rufino, M.C.; Hengsdijk, H.; Verhagen, A. Analysing Integration and Diversity in Agro-Ecosystems by Using Indicators of Network Analysis. *Nutr. Cycl. Agroecosyst.* **2009**, *84*, 229–247. [CrossRef]
28. Parsons, D.; Nicholson, C.F.; Blake, R.W.; Ketterings, Q.M.; Ramírez-Aviles, L.; Cherney, J.H.; Fox, D.G. Application of a Simulation Model for Assessing Integration of Smallholder Shifting Cultivation and Sheep Production in Yucatán, Mexico. *Agric. Syst.* **2011**, *104*, 13–19. [CrossRef]
29. Thornton, P.K.; Herrero, M. Integrated Crop–Livestock Simulation Models for Scenario Analysis and Impact Assessment. *Agric. Syst.* **2001**, *70*, 581–602. [CrossRef]
30. Martel, G.; Ramette, C.; Bouvarel, I.; Buteau, A.; Fontanet, J.-M.; Mischler, P. NiCC'El. Un outil pour caractériser le niveau d'interaction entre cultures et élevage d'une exploitation et identifier les voies d'amélioration. *Innov. Agron.* **2020**, *80*, 33–40.
31. Moraine, M.; Duru, M.; Therond, O. A Social-Ecological Framework for Analyzing and Designing Integrated Crop–Livestock Systems from Farm to Territory Levels. *Renew. Agric. Food Syst.* **2016**, *32*, 43–56. [CrossRef]
32. Schiere, H.; Kater, L. Mixed Crop-Livestock Farming. A Review of Traditional Technologies Based on Literature and Field Experience. *FAO Anim. Prod. Health Pap.* **2001**, *152*, 88.
33. Schiere, J.B.; Ibrahim, M.N.M.; van Keulen, H. The Role of Livestock for Sustainability in Mixed Farming: Criteria and Scenario Studies under Varying Resource Allocation. *Agric. Ecosyst. Environ.* **2002**, *90*, 139–153. [CrossRef]
34. Bell, L.W.; Moore, A.D. Integrated Crop–Livestock Systems in Australian Agriculture: Trends, Drivers and Implications. *Agric. Syst.* **2012**, *12*, 1–12. [CrossRef]
35. Garrett, R.D.; Ryschawy, J.; Bell, L.W.; Cortner, O.; Ferreira, J.; Garik, A.V.N.; Gil, J.D.B.; Klerkx, L.; Moraine, M.; Peterson, C.A.; et al. Drivers of Decoupling and Recoupling of Crop and Livestock Systems at Farm and Territorial Scales. *Ecol. Soc.* **2020**, *25*, 24. [CrossRef]
36. Sumberg, J. Toward a Dis-Aggregated View of Crop–Livestock Integration in Western Africa. *Land Use Policy* **2003**, *20*, 253–264. [CrossRef]
37. Agreste. RA2020-Gers-Une Agriculture plus Spécialisée En Productions Végétales. *Études Agreste* **2022**, *18*.
38. Météo-France [Daily Precipitation and Temperature Data, Auch-Lamothe Weather Station (32013005), 1987-2020][Unpublished Raw Data] 2020.
39. CACG. *Étude Pédologique de Reconnaissance Au 1/50 000-Grand Ensemble Des Baïses et Du Gers*, (Internal study report). 1965.
40. IGN Auch/Barran [1/25000 Topographic Map] 2016.
41. Lacoste, M.; Lawes, R.; Ducourtieux, O.; Flower, K. Assessing Regional Farming System Diversity Using a Mixed Methods Typology: The Value of Comparative Agriculture Tested in Broadacre Australia. *Geoforum* **2018**, *90*, 183–205. [CrossRef]
42. Barral, S.; Touzard, I.; Rasse-Mercat, É.; Ferraton, N.; Pillot, D. Assessing Smallholder Farming: Diagnostic Analysis of Family-Based Agricultural Systems in a Small Region. Available online: https://scholar.google.com/scholar_lookup?title=Assessing%20Smallholder%20Farming%3A%20Diagnostic%20Analysis%20of%20Family-based%20Agricultural%20Systems%20in%20a%20Small%20Region&author=S.%20Barral&publication_year=2012 (accessed on 23 April 2023).
43. Cochet, H. The Systeme Agraire Concept in Francophone Peasant Studies. *Geoforum* **2012**, *43*, 128–136. [CrossRef]
44. Cochet, H. *Comparative Agriculture*; Springer: Berlin/Heidelberg, Germany, 2015.
45. Crouzel, F. Auch, Carte Géologique à 1/50 000 [Geological Map] 1960.
46. Sébillotte, M. Jachère, système de culture, système de production, méthodologie d'étude. *JATBA* **1977**, *24*, 241–264. [CrossRef]
47. Landais, E.; Lhoste, P.; Milleville, P. Points de Vue Sur La Zootechnie et Les Systèmes d'élevage Tropicaux. *Cah. Sci. Hum.* **1987**, *23*, 421–437.
48. Dedieu, B. Les Systèmes d'élevage Ovins-Viande En Cévennes Gardoises: Éléments d'analyse Des Systèmes Fourragers. *Etud. Rech. Syst. Agraires Dév* **1987**, *11*, 79–87.
49. Martin, G.; Moraine, M.; Ryschawy, J.; Magne, M.-A.; Asai, M.; Sarthou, J.-P.; Duru, M.; Therond, O. Crop–Livestock Integration beyond the Farm Level: A Review. *Agron. Sustain. Dev.* **2016**, *36*, 53. [CrossRef]

50. Schiere, J.B.; De Wit, J. Livestock and Farming Systems Research II: Development and Classifications. In *Cattle, Straw and Systems Control*; Wageningen Agricultural University: Amsterdam, The Netherlands, 1995; pp. 39–61.
51. Entz, M.H.; Bellotti, W.D.; Powell, J.M.; Angadi, S.V.; Chen, W.; Ominski, K.H.; Boelt, B. Evolution of Integrated Crop-Livestock Production Systems. In *Grassland: A Global Ressource*; Wageningem Academic Publishers: Wageningem, The Netherlands, 2005; pp. 137–148.
52. Poux, X.; Narcy, J.B.; Ramain, B. The "Saltus": A Historical Concept for a Better Understanding the Relationships between Agriculture and Biodiversity Today. *Courr. L'environnement L'inra* **2009**, *57*, 23–34.
53. Spugnoli, P.; Dainelli, R. Environmental Comparison of Draught Animal and Tractor Power. *Sustain. Sci.* **2013**, *8*, 61–72. [CrossRef]
54. Fahrig, L. Effects of Habitat Fragmentation on Biodiversity. *Annu. Rev. Ecol. Evol. Syst.* **2003**, *34*, 487–515. [CrossRef]
55. Duflot, R.; Aviron, S.; Ernoult, A.; Fahrig, L.; Burel, F. Reconsidering the Role of 'Semi-Natural Habitat' in Agricultural Landscape Biodiversity: A Case Study. *Ecol. Res.* **2015**, *30*, 75. [CrossRef]
56. Tscharntke, T.; Klein, A.M.; Kruess, A.; Steffan-Dewenter, I.; Thies, C. Landscape Perspectives on Agricultural Intensification and Biodiversity—Ecosystem Service Management. *Ecol. Lett.* **2005**, *8*, 857–874. [CrossRef]
57. Gardiner, M.M.; Landis, D.A.; Gratton, C.; DiFonzo, C.D.; O'Neal, M.; Chacon, J.M.; Wayo, M.T.; Schmidt, N.P.; Mueller, E.E.; Heimpel, G.E. Landscape Diversity Enhances Biological Control of an Introduced Crop Pest in the North-Central USA. *Ecol. Appl.* **2009**, *19*, 143–154. [CrossRef]
58. Burkart, M.; James, D.; Liebman, M.; Herndl, C. Impacts of Integrated Crop-Livestock Systems on Nitrogen Dynamics and Soil Erosion in Western Iowa Watersheds. *J. Geophys. Res.* **2005**, *110*, G01009. [CrossRef]
59. Brazier, R.E.; Bilotta, G.S.; Haygarth, P.M. A Perspective on the Role of Lowland, Agricultural Grasslands in Contributing to Erosion and Water Quality Problems in the UK. *Earth Surf. Process. Landf.* **2007**, *32*, 964–967. [CrossRef]
60. Schuman, G.E.; Janzen, H.H.; Herrick, J.E. Soil Carbon Dynamics and Potential Carbon Sequestration by Rangelands. *Environ. Pollut.* **2002**, *116*, 391–396. [CrossRef]
61. Powell, J.M.; Fernández-Rivera, S.; Hiernaux, P.; Turner, M.D. Nutrient Cycling in Integrated Rangeland/Cropland Systems of the Sahel. *Agric. Syst.* **1996**, *52*, 143–170. [CrossRef]
62. Achard, F.; Banoin, M. Fallows, Forage Production and Nutrient Transfers by Livestock in Niger. *Nutr. Cycl. Agroecosyst.* **2003**, *65*, 183–189. [CrossRef]
63. Diarisso, T.; Corbeels, M.; Andrieu, N.; Djamen, P.; Tittonell, P. Biomass Transfers and Nutrient Budgets of the Agro-Pastoral Systems in a Village Territory in South-Western Burkina Faso. *Nutr. Cycl. Agroecosyst.* **2015**, *101*, 295–315. [CrossRef]
64. Khaleel, R.; Reddy, K.R.; Overcash, M.R. Changes in Soil Physical Properties Due to Organic Waste Applications: A Review. *J. Environ. Qual.* **1981**, *10*, 133–141. [CrossRef]
65. Rasmussen, J.; Søegaard, K.; Pirhofer-Walzl, K.; Eriksen, J. N2-Fixation and Residual N Effect of Four Legume Species and Four Companion Grass Species. *Eur. J. Agron.* **2012**, *36*, 66–74. [CrossRef]
66. Hendrickson, B.H.; Barnett, A.P.; Beale, O.W. Conservation Methods for Soils of the Southern Piedmont. *Agric. Inf. Bull.* **1963**, *269*, 18.
67. Sun, L.; Zhang, B.; Yin, Z.; Guo, H.; Siddique, K.H.M.; Wu, S.; Yang, J. Assessing the Performance of Conservation Measures for Controlling Slope Runoff and Erosion Using Field Scouring Experiments. *Agric. Water Manag.* **2022**, *259*, 107212. [CrossRef]
68. Schulz, F.; Brock, C.; Schmidt, H.; Franz, K.-P.; Leithold, G. Development of Soil Organic Matter Stocks under Different Farm Types and Tillage Systems in the Organic Arable Farming Experiment Gladbacherhof. *Arch. Agron. Soil Sci.* **2014**, *60*, 313–326. [CrossRef]
69. Rubio, V.; Diaz-Rossello, R.; Quincke, J.A.; van Es, H.M. Quantifying Soil Organic Carbon's Critical Role in Cereal Productivity Losses under Annualized Crop Rotations. *Agric. Ecosyst. Environ.* **2021**, *321*, 107607. [CrossRef]
70. Johnston, A.E.; Poulton, P.R.; Coleman, K.; Macdonald, A.J.; White, R.P. Changes in Soil Organic Matter over 70 Years in Continuous Arable and Ley-Arable Rotations on a Sandy Loam Soil in England: Carbon Sequestration and Losses over 70 Years. *Eur. J. Soil Sci.* **2017**, *68*, 305–316. [CrossRef]
71. Libohova, Z.; Seybold, C.; Wysocki, D.; Wills, S.; Schoeneberger, P.; Williams, C.; Lindbo, D.; Stott, D.; Owens, P.R. Reevaluating the Effects of Soil Organic Matter and Other Properties on Available Water-Holding Capacity Using the National Cooperative Soil Survey Characterization Database. *J. Soil Water Conserv.* **2018**, *73*, 411–421. [CrossRef]
72. Boyle, M.; Frankenberger, W.T., Jr.; Stolzy, L.H. The Influence of Organic Matter on Soil Aggregation and Water Infiltration. *J. Prod. Agric.* **1989**, *2*, 290–299. [CrossRef]
73. Garnier, J.; Anglade, J.; Benoit, M.; Billen, G.; Puech, T.; Ramarson, A.; Passy, P.; Silvestre, M.; Lassaletta, L.; Trommenschlager, J.-M.; et al. Reconnecting Crop and Cattle Farming to Reduce Nitrogen Losses to River Water of an Intensive Agricultural Catchment (Seine Basin, France): Past, Present and Future. *Environ. Sci. Policy* **2016**, *63*, 76–90. [CrossRef]
74. Lantinga, E.A.; Boele, E.; Rabbinge, R. Maximizing the Nitrogen Efficiency of a Prototype Mixed Crop-Livestock Farm in The Netherlands. *NJAS Wagening. J. Life Sci.* **2013**, *66*, 15–22. [CrossRef]
75. Randall, G.W.; Huggins, D.R.; Russelle, M.P.; Fuchs, D.J.; Nelson, W.W.; Anderson, J.L. Nitrate Losses through Subsurface Tile Drainage in Conservation Reserve Program, Alfalfa, and Row Crop Systems. *J. Environ. Qual.* **1997**, *26*, 1240–1247. [CrossRef]
76. Hoeffner, K.; Beylich, A.; Chabbi, A.; Cluzeau, D.; Dascalu, D.; Graefe, U.; Guzman, G.; Hallaire, V.; Hanisch, J.; Landa, B.B. Legacy Effects of Temporary Grassland in Annual Crop Rotation on Soil Ecosystem Services. *Sci. Total Environ.* **2021**, *780*, 146140. [CrossRef] [PubMed]

77. Liebman, M.; Dyck, E. Crop Rotation and Intercropping Strategies for Weed Management. *Ecol. Appl.* **1993**, *3*, 92–122. [CrossRef] [PubMed]
78. Martin, G.; Durand, J.-L.; Duru, M.; Gastal, F.; Julier, B.; Litrico, I.; Louarn, G.; Médiène, S.; Moreau, D.; Valentin-Morison, M.; et al. Role of Ley Pastures in Tomorrow's Cropping Systems. A Review. *Agron. Sustain. Dev.* **2020**, *40*, 17. [CrossRef]
79. Akram, U.; Quttineh, N.-H.; Wennergren, U.; Tonderski, K.; Metson, G.S. Enhancing Nutrient Recycling from Excreta to Meet Crop Nutrient Needs in Sweden–a Spatial Analysis. *Sci. Rep.* **2019**, *9*, 1–15. [CrossRef]
80. van der Werf, H.M.G.; Petit, J.; Sanders, J. The Environmental Impacts of the Production of Concentrated Feed: The Case of Pig Feed in Bretagne. *Agric. Syst.* **2005**, *83*, 153–177. [CrossRef]
81. Mallin, M.A.; Cahoon, L.B. Industrialized Animal Production—A Major Source of Nutrient and Microbial Pollution to Aquatic Ecosystems. *Popul. Environ.* **2003**, *24*, 369–385. [CrossRef]
82. Tamminga, S. Pollution Due to Nutrient Losses and Its Control in European Animal Production. *Livest. Prod. Sci.* **2003**, *84*, 101–111. [CrossRef]
83. Agence bio Les Chiffres 2021 Du Secteur Bio. Dossier de Presse Juin 2022. Available online: https://www.agencebio.org/wp-content/uploads/2022/07/DP_LAGENCE-BIO-26-07_22.pdf (accessed on 22 March 2023).
84. Agence bio La Bio En France, de La Production à La Consommation. Available online: https://www.agencebio.org/sites/default/files/upload/documents/4_Chiffres/BrochureCC/CC2011_Partie2.pdf (accessed on 22 June 2023).
85. Billen, G.; Le Noë, J.; Anglade, J.; Garnier, J. Polyculture-Élevage Ou Hyper-Spécialisation Territoriale? Deux Scénarios Prospectifs Du Système Agro-Alimentaire Français. Innovations. *Innov. Agron.* **2019**, *72*, 31–44.
86. Schut, A.G.T.; Cooledge, E.C.; Moraine, M.; Van De Ven, G.W.J.; Jones, D.L.; Chadwick, D.R. Reintegration of Crop-Livestock Systems in Europe: An Overview. *Front. Agric. Sci. Eng.* **2021**, *8*, 111. [CrossRef]
87. Stark, F.; González-García, E.; Navegantes, L.; Miranda, T.; Poccard-Chapuis, R.; Archimède, H.; Moulin, C.-H. Crop-Livestock Integration Determines the Agroecological Performance of Mixed Farming Systems in Latino-Caribbean Farms. *Agron. Sustain. Dev.* **2018**, *38*, 4. [CrossRef]
88. Poux, X.; Aubert, P.-M. An Agroecological Europe in 2050: Multifunctional Agriculture for Healthy Eating. Findings from the Ten Years For Agroecology (TYFA) Modelling Exercise. *IDDRI Studies* **2018**, *09*, 18.
89. Devendra, C. Crop Residues for Feeding Animals in Asia: Technology Development and Adoption in Crop/Livestock Systems. In *Crop Residues in Sustainable Mixed Crop/Livestock Farming Systems*; CAB International: Wallingford, UK, 1997; pp. 241–267.
90. Barbieri, C.; Mahoney, E.; Butler, L. Understanding the Nature and Extent of Farm and Ranch Diversification in North America*. *Rural. Sociol.* **2008**, *73*, 205–229. [CrossRef]
91. Garrett, R.; Niles, M.; Gil, J.; Dy, P.; Reis, J.; Valentim, J. Policies for Reintegrating Crop and Livestock Systems: A Comparative Analysis. *Sustainability* **2017**, *9*, 473. [CrossRef]
92. Herrero, M.; Thornton, P.K.; Notenbaert, A.; Msangi, S.; Wood, S.; Kruska, R.; Dixon, J.; Bossio, D.; van de Steeg, J.; Freeman, H.A.; et al. *Drivers of Change in Crop–Livestock Systems and Their Potential Impacts on Agro-Ecosystems Services and Human Wellbeing to 2030*; ILRI: Nairobi, Kenya, 2012; p. 114.
93. Moraine, M.; Duru, M.; Nicholas, P.; Leterme, P.; Therond, O. Farming System Design for Innovative Crop-Livestock Integration in Europe. *Animal* **2014**, *8*, 1204–1217.