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Fostering local crop-livestock integration via legume exchanges using an innovative integrated assessment and modelling approach based on the MAELIA platform

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ABSTRACT

CONTEXT: Crop diversification is now well-recognised as a strong lever to address the environmental challenges currently faced by agriculture. Connecting and fostering local exchanges between specialised arable crop and livestock farms can support the diversification of crops and relocate animal feeding with local protein (vs. soya supplements). However, the trade-offs and synergies between individual and collective objectives and performances generated by this system are still largely unknown. Innovative tools that consider the spatiotemporal heterogeneity underpinning the daily functioning of farms are needed to explore the implications of exchange scenarios.
OBJECTIVES: To assess self-sufficiency, sustainability and vulnerability at the farm, group (arable vs. livestock) and territorial levels considering the baseline situation and scenarios that increase synergy between arable and livestock farms.
METHODS: We demonstrated the utility of using MAELIA, a spatial agent-based integrated modelling framework, to support iterative design and assessment of self-sufficiency, sustainability and vulnerability of such scenarios. MAELIA was applied to model a collective of five arable and two livestock farmers in western France. In a participatory approach, scientists, agricultural advisers and the farmers co-designed three possible scenarios of legume exchanges.
RESULTS AND CONCLUSIONS: Only the most ambitious scenario based on strong collaboration allowed farmers to reach local protein self-sufficiency while reducing the variability in five of the seven indicators used to assess farm performances. Meeting livestock farms' demand for legumes had a positive influence on socio-economic performance at the territorial level, including an increase in the mean gross margin (of 71 €/ha; 4% higher), decrease in the use of nitrogen fertiliser (of ca. 21 kg N/ha; 11% lower) and decrease in labour time (of ca. 12 min/ha; 5% lower). No major trade-offs between self-sufficiency and vulnerability were observed. However, there were distinct individual performances related to the degree of changes imposed on each farm.
SIGNIFICANCE: We show that by reducing the dependence to external inputs, these systems are promising alternatives to an environmentally sustainable, resilient and economically viable agroecological transition. The development of dedicated institutional support for direct bilateral or multilateral agreements, and specific financial and technical support would encourage farmers to join such initiatives and redesign their farming systems.

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1. Introduction

Modern intensive agriculture, through its direct impacts on land-use patterns and ecosystems, faces unprecedented sustainability challenges that require an agroecological transition (Barnosky et al., 2012; Dainese et al., 2019). Mixed or integrated crop-livestock systems (ICLS) are a promising sustainable production model to address challenges of resource depletion and other negative impacts of agriculture, without hindering farm economics (Herrero et al., 2010; Martin et al., 2016). ICLS have ecological (Lemaire et al., 2014) and economic benefits (Ryschawy et al., 2013) when crop and livestock interact strongly over space and time (Bell et al., 2014; Moraine et al., 2016b). ICLS can stabilise yields and ensure farm resilience against market and climate fluctuations (Peyraud et al., 2014; Weindl et al., 2015). However, ICLS have continuously decreased in number despite these benefits. In 2016, mixed crop-livestock holdings represented less than one-fifth of farms in the European Union (Eurostat, 2018). The three key drivers behind this decrease include standardisation of production with high agronomic potential (based on synthetic inputs, high-performing and specialised machinery, and animal housing systems), agricultural subsidies oriented towards specialised systems and simplification of workload (Garrett et al., 2020). The prohibitive cost of converting farms makes it unlikely that specialised farms will re-adopt mixed systems (Martin et al., 2016; Peyraud et al., 2014). Accordingly, recent research has highlighted the potential to develop spatiotemporal interactions between arable and livestock farms through exchanges between specialised farming systems (i.e. at the territorial level) (Asai et al., 2018; Martin et al., 2016; Moraine et al., 2016a; Ryschawy et al., 2018; Ryschawy et al., 2017).

From this perspective, the challenge is to design a territorial crop-livestock system (TCLS) that is considered a social-ecological system (Moraine et al., 2016a). Unlike a farm-level approach, the territory level (as defined by Moraine et al. (2016b), Moraine et al., 2016a) and used herein) includes several farms that interact in a local geographic area. Moraine et al. (2016a) and Martin et al. (2016) distinguished three forms of TCLS integration that depend on the level of spatial, temporal and organisational relationships between specialised farms: local coexistence, complementarity and synergy. While the first form involves only market-mediated cooperation driven by pure economic logic, the second and third forms are based on local interactions between farms that do or do not share resources (e.g. land and equipment). Moraine et al., (2017) and Asai et al. (2018, 2014) identified that farmers consider the spatial proximity of farms to be the main factor that leads to successfully coordinated arrangements and thus to stable trustworthy relationships. Furthermore, cooperation between specialised farms can provide access to otherwise unavailable or underutilised local resources, such as land and livestock feed (Regan et al., 2017). Thus, establishing direct and local markets could address current limitations of specialised supply chains (Moraine et al., 2016b), while also increasing economic (Moraine et al., 2017) and resource-use efficiency (Regan et al., 2017). However, the implementation and sustainability of TCLS integration are considered socially and technologically challenging (Asai et al., 2018; Moraine et al., 2016b).

The critical factors that influence the implementation, development and sustainability of TCLSs remain largely unknown (Moraine et al., 2016a). One major obstacle is the lack of operational tools to support the design of the necessary socio-technical changes (Asai et al., 2018; Martin et al., 2016; Moraine et al., 2016b). It is necessary to develop and evaluate innovative and feasible cropping and livestock systems that are consistent with the specific characteristics of farms, territories and local supply-chains (Moraine et al., 2016b). It should also be possible to identify trade-offs and synergies between individual and collective objectives and performances (Ryschawy et al., 2017). Most current modelling tools fail to consider the main characteristics of TCLS (Martin et al., 2016; Ryschawy et al., 2017). For example, Fernandez-Mena et al. (2020a), Fernandez-Mena et al., 2020b) recently developed an agent-based model, while Jouan et al. (2020) developed a non-linear bio-economic model, to assess scenarios of exchanges between farms. However, these studies did not consider the spatiotemporal heterogeneity of biophysical processes on farms that underpins the daily functioning of TCLS or the decision-making process of farmers. Thus, a major weakness is the lack of spatially explicit and dynamic representations of interactions among the soil, climate and cropping systems (i.e. crop rotations and management) on farms, which conceals intra- and inter-annual variability in exchanges between farms (Martin et al., 2016). They also do not identify supply-demand imbalances that occur within and over a year or assess the system's resilience and vulnerability. To address this limitation, Martin et al. (2016) suggested developing a locally adapted decision support system that includes dynamic spatially explicit simulation of TCLS scenarios to reduce the risk of farmers' uncertainties about implementing a TCLS and their aversion to risk. Considering stakeholders' real constraints and identifying consensual solutions would encourage acceptance of innovations and their implementation in practice (McGranahan, 2014).

We address this methodological gap by demonstrating the utility of using an agent-based platform for integrated assessment and modelling (IAM), MAELIA, to support iterative design and assessment of TCLS scenarios involving farmers, agricultural advisers and scientists (Therond et al., 2014). MAELIA is a significant advancement in TCLS modelling as it represents (i) daily dynamics of interactions among the soil, climate and crop rotation in each field of each farm considered, (ii) crop management strategies described in detail per farmer, cropping system and crop, and (iii) use of simple and robust pattern-based models of biophysical processes.

Our case study consisted of a collective of seven neighbouring farms in the district of Pays de Pouzauges (Vendée department, western France): five arable and two livestock (dairy cattle) farms. Three scenarios were co-designed that represented a gradient of spatiotemporal interactions between the two types of farms. MAELIA was used to assess self-sufficiency, sustainability and vulnerability at the farm, group (arable vs. livestock) and territorial levels (Fig. 1). The results focused on (i) the performance of the *baseline situation* compared to scenarios that increased territorial synergy between crop and livestock farms and (ii) factors that increase the resilience of farm production and profitability against economic shocks. Finally, we discuss socio-economic and agroecological benefits of TCLS, factors that support or limit farmers' synergistic engagement, and strengths and necessary improvements for our IAM method. At the policy level, we discuss socio-economic factors that support or restrict farmers' participation in exchanges.

2. Materials and methods

2.1. The modelling platform: MAELIA

MAELIA is a high-resolution agent-based platform for IAM of agricultural landscapes considered as socio-agroecological systems (Therond et al., 2014). One of MAELIA's main innovations is to simulate daily spatiotemporal dynamics of agricultural technical operations at the field level within the landscape considering (i) the diversity of farming strategies, (ii) spatial intra- and inter-annual weather variability and spatial variability of soils and (iii) ecological processes (e.g. crop growth, water cycle and irrigation, Murgue et al., 2014; Rizzo et al., 2019; Therond et al., 2014, Therond et al., 2011). We used the part of the modelling chain of MAELIA that consists of a farm-agent model coupled with a cropping system model.

The farm-agent model simulates daily dynamics of technical operations in each field and considers soil, climate and plant states and farm-level constraints. These constraints are related to each operation's execution time, the spatial distribution of fields and the priorities of activities (Murgue et al., 2014; Therond et al., 2014). The crop management strategy is represented using a set of nested IF-THEN-ELSE statements. They correspond to realistic decision rules obtained from a survey of farmers (Supp. Methods 1).

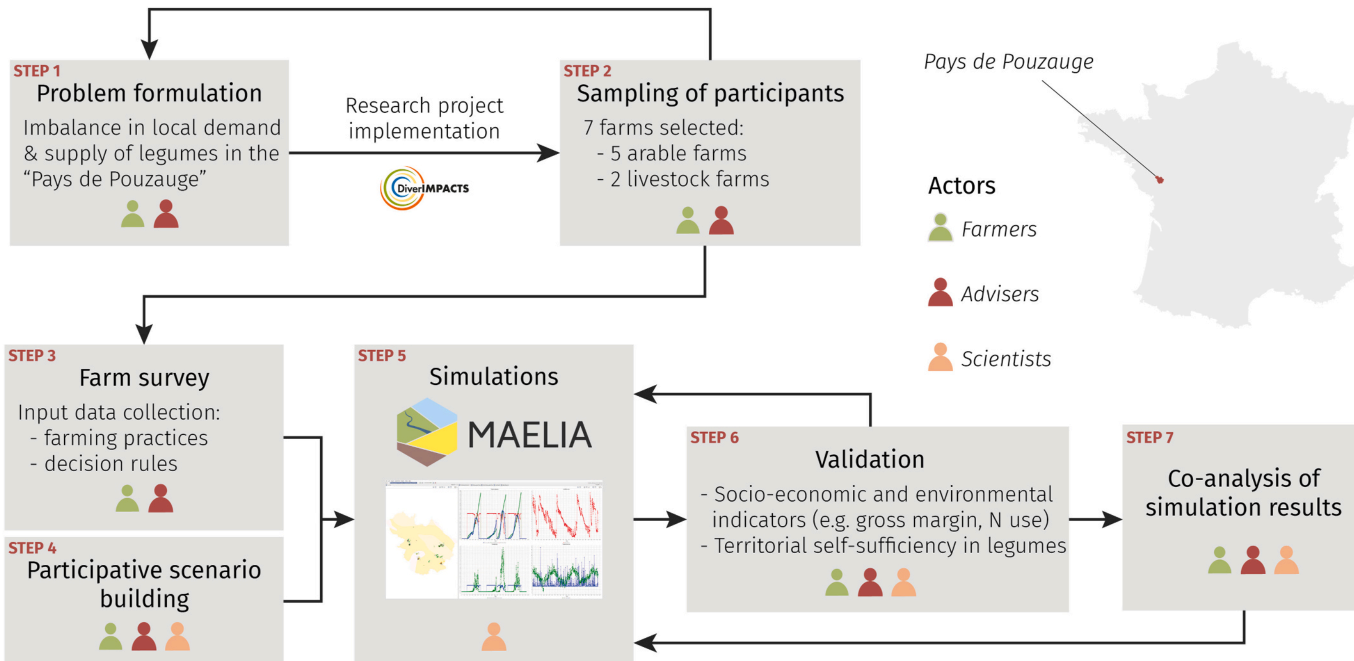

Fig. 1. Summary of the workflow and stakeholders involved to design and assess with MAELIA the territorial crop-livestock system (TCLS) studied. After formulating a general problem (step 1), the problem was specified according to the goals of each of the seven farmers selected (step 2). After farm surveys (step 3), the scenarios were designed via a participatory process (step 4). Outcomes of the survey and the scenario exercise were used as an input in the MAELIA simulation platform (step 5). Simulation results were then aggregated at several spatio-temporal scales to allow agricultural advisers to evaluate their consistency (step 6). Steps 5 and 6 were repeated until MAELIA was calibrated. The final results were then compiled and disseminated to farmers (step 7). The location of the TCLS case study is shown on the top right corner (see also Supp. Fig. 2).

Crop-soil dynamics are modelled with a generic cropping system model (AqYield) that represents each field of each farm and simulates daily interactions between the soil water cycle, climate, farming practices and crop growth (Constantin et al., 2015; Tribouillois et al., 2020). The final crop yield is modelled as a function of the ability to meet water requirements throughout the entire growth cycle (see Constantin et al., 2015, appendix A, for a complete description of AqYield). All crops and cover crops (winter oats, mixed cereals, ryegrass and lucerne) were simulated with AqYield. MAELIA can predict the effects of farming system changes (e.g. in crop rotation, crop management, climate or economic scenarios) on daily interactions between crop management and growth from field to farm levels. As in most studies (e.g. Moraine et al., 2017; Moraine et al., 2016b; Ryschawy et al., 2018), we did not simulate dynamics of farmers' behaviour in the local vs. global market, as the types and expected amounts of exchanged products were defined in the co-designed scenarios.

MAELIA provides several output indicators (e.g. input use, irrigation water, agricultural production, gross margin, the workload of crop management operations) and can provide intermediate variables for specific case studies (e.g. soil water content, water stress; see example in Allain et al., 2018). Simulated scenarios can be developed in the laboratory or through participatory approaches that consider stakeholders' real constraints and solutions that they consider acceptable (Allain et al., 2018; Murgue et al., 2016). When applied in participatory approaches, MAELIA can be used to support the iterative design and integrated assessment of scenarios (see Murgue et al., 2014; Martin et al., 2017). Previous studies have focused on MAELIA's development (Therond et al., 2014) and calibration (Lardy et al., 2014; Mazzega et al., 2014; Murgue et al., 2014), as well as the development of the participatory design-and-assessment method for agricultural landscape scenarios (Allain et al., 2018; Murgue et al., 2016; Murgue et al., 2015).

2.2. Case study description

The case study is part of the DiverIMPACTS project (https://www.diverimpacts.net/case-studies/case-study-11-fr.html), which was based on existing and newly developed initiatives related to crop diversification in Europe. Based on farm visits performed by two agricultural advisers of the Regional Chamber of Agriculture of Pays de la Loire (CRAPL, in French) in 2016, a collective of seven neighbouring farms that wished to develop local exchanges was identified. They expressed specific objectives to reduce dependence on the global market (e.g. for nitrogen (N) fertilisers and soya bean meal), reduce economic variability and increase self-sufficiency in animal feed. The supply of manure was not considered relevant, as it was not a limiting factor for the arable farmers involved.

The seven farms included five arable farms (AFs: AF1, AF2, AF3, AF4 and AF5) and two livestock farms (LFs: LF1 and LF2, with 65 and 110 dairy cows, respectively) that also produced arable crops (Supp. Fig. 1). The study area was located in the district of Pays de Pouzauges in the Vendée department (western France, Supp. Fig. 2). Over the past 30 years, the district's mean annual temperature was 12.1 °C (min: 7.8 °C and max: 16.4 °C), and mean annual rainfall was 881 mm. Its agricultural landscape is composed predominantly of grasslands (42% of the department's 480,000 ha of utilised agricultural area (UAA); Chambagri, 2019) used for livestock grazing. Its arable land is occupied mainly by intensive cereal production (35% of the UAA, mainly wheat (63%) and grain maize (24%), while protein crops, such as fava beans (*Vicia faba* L.) or peas (*Pisum sativum* L.)., occupy <1% (Chambagri, 2019). Irrigation, which is not common, is used mainly for maize (grain and silage). The district's mean farm size is 79 ha, with ca. 30 fields per farm. Of its ca. 7500 farms in 2017, ca. 45% are considered specialised cattle farms (that also produce forage crops), 14% produce poultry, 14% are specialised AFs, 7% are mixed livestock-crop farms, 8% produce other livestock species and 12% are other agricultural systems (Chambagri, 2019). In our case study, farms ranged in size from 43 to 138 ha (mean

100 ± 34 ha), with ca. 28 ± 11 fields. These values are representative of the larger scale of the Vendee department.

2.3. Case study implementation

The design-and-assessment method using MAELIA is based on integrating generic and local knowledge to find novel and satisfying solutions for social-ecological systems rather than to obtain mathematically optimal solutions (Murgue et al., 2016; Murgue et al., 2015). In this context, we directed our research based on the interest that the farmers expressed during several meetings with the agricultural advisers from CRAPL. Through farm surveys performed in March and April 2019, information about crop management decision rules and general information about the farms (e.g. crops, agricultural equipment, average crop yields) was collected for the period from July 2014 to September 2018. General farm characteristics obtained from the survey differed between AFs and LFs (Table 1, Supp. Table 1).

An additional form with the survey was used to obtain information about each farmer's decision rules. These rules described the conditions required to trigger each crop operation and the temporal window during which it can be performed, depending on soil, crop and/or climate conditions (Supp. Methods).

The French Land Parcel Identification System (LPIS) (v2017), a geographical database (Grandgirard and Zielinski, 2008; IGN-Institut National de l'Information Géographique et Forestière, 2018), was used to provide the boundaries of fields and field blocks of each farm investigated (Supp. Fig. 2). With the farmers, we finely adjusted the field boundaries and ownership, identified rain-fed and irrigated fields, and reconstructed the fields' crop rotations (main and cover crops associated with all spring crops). This process identified 70 different crop rotations implemented on the fields of the seven farms. Two farmers (AF1 and LF1) used an irrigation system for silage maize at the recommended rate of four applications of 300 m^3/ha each year.

Climate data were obtained from the SAFRAN dataset (8 km × 8 km) of Météo France (Vidal et al., 2010). General soil data were obtained from the European Soil Database v2 at the 1:1,000,000 scale (European Soil Data Centre, 2019; Panagos et al., 2012). When available, soil data were improved using soil analyses provided by the farmers. Spatially intersecting data layers for field boundaries from the LPIS with soil and climate data provided a consistent description of the soil and climate characteristics of each field (Murgue et al., 2016).

Economic information (crop prices, premiums and input costs) was provided by agricultural advisers from CRAPL for 2015, 2016 and 2017. Economic information for the remaining simulated period (2005–2014) was extrapolated using the agricultural producer price index for each year for each input and output (INSEE, 2020).

Soil-crop dynamics for both AFs and LFs were simulated using the same formalisms. AFs supplied any deficits in animal feed ingredients required by each LF. The dynamics of livestock growth and grazing were not considered as they lay outside the scope of this study. Similarly, variation in forage inputs in the LFs, which would influence annual or seasonal demand for feedstock (protein and energy), was not considered. Based on the agricultural advisers' expertise, we assumed that (i) each LF had a constant number of cows in lactation, each of which was fed a custom feed formula for nine months (Supp. Table 2); (ii) the quantity and quality of milk produced, and thus milk prices, were constant during the lactation period for both LFs' herds (Supp. Table 2); and (iii) cows bred for replacement and dry cows grazed grasslands, supplemented with fodder and hay. Furthermore, according to the agricultural advisers and farmers, grassland grazing and forage were not limiting factors for the LFs studied. Finally, based on information provided by the agricultural advisers, permanent and temporary grasslands were assumed to produce 10 t of fresh matter per ha per year, divided into three cuts: 5 t (used as fodder), 3 t and 2 t (used as hay).

Table 1
Descriptive statistics of the seven farms studied in the baseline situation over the medium-term period from August 2004 to December 2017.

Characteristic	Arable farms ($n = 5$)			Livestock farms ($n = 2$)		
	Mean (±SD)	Min	Max	Mean (±SD)	Min	Max
Farm area (ha)	95 ± 37	43	138	112 ± 31	90	134
Utilised agricultural area (ha)	70 ± 22	43	103	70 ± 3	68	72
Total revenue (€/ha)	1648 ± 577	704	3825	5191 ± 1112	3353	8709
Gross margin (€/ha)	1365 ± 582	471	3506	3596 ± 745	2399	6779
Total variable costs (€/ha)	283 ± 53	175	392	1595 ± 457	810	2637

SD: standard deviation

2.4. Designing the scenarios

Scenarios were developed via participatory collaboration with all of the stakeholders involved (the seven farmers and three agricultural advisers from the CRAPL). The scenarios were used to evaluate the ability of AFs to meet the needs for new animal feed formulations in the LFs given different levels of change in the AFs' cropping systems. The agricultural advisers designed the new animal feed formulations for the two livestock farmers (LF1 and LF2) to maintain baseline milk production while replacing soya bean meal and cereal grain mix with fava beans or peas. The diet formulation was updated to decrease the dependence on foreign markets (soya bean meal) by incorporating local protein sources and decrease the total cost of feeding (Supp. Table 2). The AFs chose fava beans and peas (Fabaceae family) as they needed a crop from a different family to diversify their current crop rotations (composed mainly of grasses, Poaceae family) to respond to wheat diseases and/or high weed pressure. From experiences that the advisers collected from other farmers, these two legumes are better adapted to the region (without irrigation) than soya bean or other pulses because they show positive results (e.g. reduction in inputs) at the rotation scale.

The *baseline situation* considered the current production situation, in which farmers do not trade with each other, and LFs use the baseline animal feed formulation based on protein from soybean meal complimented by cereal grains. Based on Martin et al. (2016)'s descriptions of types and levels of TCLS, three scenarios were co-designed:

- *Coexistence scenario*: a local market among farmers is created based on local coexistence driven by pure economic supply-demand reasoning and with no change in cropping systems on AFs. Livestock farmers meet their demand for feed ingredients from arable farmers given their baseline production levels. Hence, this scenario had the same crop production as the *baseline situation*.
- *Complementarity scenario*: a level of complementarity is developed to meet livestock farmers' demand for feed ingredients. Arable farmers introduce spring peas and fava beans into their rotations before winter wheat and between cereals (e.g. winter wheat, spring or winter barley, triticale, winter oats).
- *Synergetic scenario*: to develop territorial synergy, arable farmers perform pre-established and collaborative decision-making at the field level about who grows which crop rotations to meet the demand completely and continuously. If more legumes need to be produced, they are introduced in up to three prioritised steps in the crop rotations: legumes can be (i) followed by any winter cereal, but preferentially winter wheat (as in the *complementarity scenario*); (ii) placed between maize and winter wheat; or (iii) followed by any cereal.

We assumed that fields with permanent grassland in the *baseline situation* did not change in the other scenarios. Legume crops were introduced infrequently in the new rotations due to maximum limits defined by the farmers: winter peas and fava beans were sown once every four years, and spring peas were sown once every three years. Priority for producing a given legume was given to the arable farmers who already produced it. The new cropping systems were translated into modified model inputs (e.g. new rules for crop rotations and management).

Crop prices and fertiliser application following legumes did not differ among scenarios. We also assumed that once livestock feeding needs were met, arable farmers would sell surplus crop yields on the regular market. Milk prices also did not differ among scenarios, as the new formulation was designed to maintain the same level of milk production and quality. To ensure comparable results, MAELIA was run to assess the *baseline situation* and each scenario. Overall, formulating the problem, designing the scenario, and calibrating and analysing the results involved 16 participants (five arable and two livestock farmers, three agricultural advisers and six scientists).

2.5. Simulation, calibration and validation through a participatory approach

MAELIA simulated the medium-term period from August 2004 to December 2017, which was suitable for considering the effects of interactions between cropping systems and climate variability. This 13-year period was chosen based on the data available (e.g. price indices). It was also twice as long as the longest crop rotation when legumes were included (i.e. six years).

The results of MAELIA simulations, including the consistency of economic and production results, were calibrated and validated in interaction with the agricultural advisers. We concluded that the results were consistent with their expert knowledge and with average yields and economic returns at the regional level. This process required several physical and virtual meetings. The meetings were used to verify and adapt MAELIA inputs for cropping system distribution, soil and climate conditions and specific decision rules for the organisational aspects within and among farms. One workshop involving the farmers in the study, agricultural advisers and one scientist was organised to present findings of the study and develop interpretations. Calibrating and validating MAELIA with relevant stakeholders is crucial because it enables fine-tuning of model parameters (crop model and decision rules) and thus simulating current farming systems given realistic assets and constraints (Murgue et al., 2016).

2.6. Indicators

Based on the interests of farmers and advisers and previous studies that address TCLS assessment, nine criteria and associated indicators (Table 2, Supp. Table 3) were selected to assess the system's self-sufficiency and sustainability. The self-sufficiency in producing each ingredient in the animal feed formulation was assessed using two indicators of the supply:demand ratio for feed quantity and PDIN (i.e. digestible protein absorbed in the small intestine, which is essential for milk production, (Vérité and Peyraud, 1988).

Based on four criteria, seven indicators were used to assess the average sustainability performance (Table 2, Supp. Table 3). Two indicators of production (energy and protein yield) were used to evaluate each farm's productivity as the energy and protein contents of its crops, as raw yields of different crops cannot be summed at the farm level. Economic performance was assessed using two indicators (gross margin and economic efficiency of production) to evaluate whether new scenarios would influence profitability and potentially reduce the dependence on external inputs, and thus the economic susceptibility to external shocks and market fluctuations. Environmental impact was assessed as the amount of inputs (N use and total amount of active ingredients in the pesticides applied). These indicators were also a proxy for the risk of health impacts (e.g. contamination of surface water by nitrate leaching). Lastly, the social impact was evaluated using a workload indicator.

Table 2
Indicators assessed, description, level of assessment and references.

Indicator	Description	Levels	Source
Self-sufficiency			
Production self-sufficiency in animal feed	Crop production based on animal feed produced on a dry matter (t/ha) basis to meet the annual needs. Self-sufficiency is attained when the supply:demand ratio exceeds 100%.	Livestock farm, Territory	Adapted from Martin et al. (2017)
Protein self-sufficiency in animal feed	Crop production of PDIN (kg/t of dry matter) based on animal feed produced to meet the annual needs. Self-sufficiency is attained when the supply:demand ratio exceeds 100%.	Livestock farm, Territory	
Performance			
Energy yield	Amount of energy contained in crop yields per year. Energy content is an important characteristic of crop yields. It is a proxy of the overall production capacity of the system.	Farm, Group, Territory	Adapted from Villalobos et al. (2016)
Protein yield	Amount of protein contained in crop yields per year. The protein content is an important characteristic of crop yields for animal feeding. It is a proxy of the production capacity for animal feeding.	Farm, Group, Territory	Adapted from Martin et al. (2017)
Gross margin	Average gross margin. Assessment of overall economic returns calculated as total revenue (including European Union subsidies) minus variable production costs (e.g. seeds, fertiliser, pesticides).	Farm, Group, Territory	Adapted from Moraine et al. (2016b)
Economic efficiency (EEP)	Economic efficiency of production per ha per year (i.e., the ratio of gross margin to total revenue). This indicator specifies the dependence on external inputs, hence the economic vulnerability to external shocks and market fluctuations. The higher the EEP, the lower is the vulnerability of the system.	Farm, Group, Territory	Adapted from Lebacq et al. (2015)
Nitrogen use	Sum of nitrogen fertiliser use on arable crops per ha per year. It is a proxy of environmental impact. The lower the nitrogen use, the lower is the environmental impact.	Farm, Group, Territory	Adapted from Moraine et al. (2016b)
Quantity of active ingredients applied	Sum of the quantities of active ingredients applied per ha per year. This indicator is a proxy of the risk of several environmental and social impacts. It includes all the insecticide, herbicide and fungicide treatments applied. Lower values indicate a lower risk of transfer to surface water, groundwater and air, and less impact on human health.	Farm, Group, Territory	Adapted from Hossard et al. (2017)

(*continued on next page*)

Table 2 (*continued*)

Indicator	Description	Levels	Source
Workload (WL)	Sum of hours per year spent on arable field activities. It is a social proxy, as a lower WL indicates that the farmer has more free time for other activities.	Farm, Group, Territory	Adapted from Moraine et al. (2016b)
Vulnerability			
Average (μ)	Overall average of the annual values of each indicator. Standard deviation is also estimated to measure the amount of variation around this overall average.	Farm, Group, Territory	Adapted from Martin et al. (2017)
Slope of the linear regression (β)	Trend of the estimated annual indicator values during the study period. It is used to assess the overall evolution in each indicator. A positive slope (or trend) indicates a positive effect for production and protein self-sufficiency for animal feed, energy and protein yield, gross margin, and economic efficiency. Conversely, a negative slope (or trend) indicates a positive effect for nitrogen use, quantity of active ingredients applied, and workload.	Farm, Group, Territory	Adapted from Martin et al. (2017)
Sum of squared residues (*SSR*)	The average deviation, i.e. variability, around the overall trend of the annual indicator values. Higher values indicate higher variability.	Farm, Group, Territory	Adapted from Martin et al. (2017)

The level and dynamics of each indicator were assessed using the vulnerability assessment framework of Martin et al. (2017). All performance and vulnerability indicators were calculated per hectare.

In addition to assessing the self-sufficiency and sustainability indicators, dynamics of these indicators over the years were assessed by adapting the method developed by Martin et al. (2017) to analyse farm vulnerability. For each indicator, two metrics were assessed in addition to the average (and standard deviation): the slope of the linear regression over time of the annual indicator values (which represented the trend) and mean residues of the regression (which represented variability in the trend of the annual indicator values; Table 2, Fig. 2). This approach assessed vulnerability by considering the overall trend, temporal trend and variability. For example, for gross margin, the combination of a viable average, a positive or constant trend, and low variability is expected when economic vulnerability decreases or resilience (considered here as the inverse of vulnerability) increases. This innovative approach differed from mainstream static evaluations of vulnerability (Martin et al., 2017), which often concentrate on measuring the overall variation in indicators (e.g. yield and profitability in Moraine et al. (2016b)) and ignore the trend of the performances considered. It also allowed us to distinguish trade-offs among three complementary metrics that underpin vulnerability.

The indicators were calculated at the farm (individual farm), group (AFs or LFs) and territory (all farms) levels (Table 2). Focusing on the farm level helps to compare performances among farms and to identify factors that influence performances (e.g. crop rotation). The group level enables performances of LFs and AFs to be analysed. The territory level, which includes all of the farms, enables the total impact of the changes to be analysed regardless of the type of farm. The statistical significance of differences between the *baseline situation* and the three scenarios was assessed using a paired sample *t*-test.

3. Results

3.1. Overview of livestock farm cost and self-sufficiency in animal feed

Feed supplements (e.g. *soya* bean meal and concentrates) in the baseline formulation represented 38% and 48% of the total feeding cost for LF1 and LF2, respectively. In the new formulations, soya bean meal was replaced by including ca. 15% peas for LF1 and 17% fava beans for LF2, which decreased annual feed costs by 16% and 7% per cow per year for LF1 and LF2, respectively (Supp. Table 2).

According to the agricultural advisers, grass fodder and hay are not a limiting factor, as both LFs produced a sufficient amount of them, in quantity and in PDIN, to meet the needs of their herds throughout the modelling period for both feed formulations (Supp. Fig. 3). For maize silage, with the baseline crop rotation, LF1 needed to obtain 91 t (55% of needs) elsewhere in 2013, whereas LF2 needed to obtain 5, 92 and 153 t (2%, 35% and 58%, respectively) elsewhere in 2006, 2010 and 2016, respectively (Supp. Fig. 3a). In the other years, maize silage production was sufficient to meet their demand. With the new feed formulation, only the availability of legumes became limiting (Table 3). As the LFs did not produce legumes, all of the new demand had to be met through local exchanges.

3.2. Self-sufficiency in coexistence and complementarity scenarios of TCLS

In the *coexistence scenario*, simply promoting exchanges between AFs and LFs did not meet the demand for legumes in the new animal feed (Fig. 2). Specifically, no AFs produced fava beans, and the baseline production of peas (by AF3) was not sufficient throughout the modelling period to meet the needs of LF1 (Table 3). Conversely, the maize silage provided by the AFs was sufficient to meet the needs of both LFs.

The *complementarity scenario* yielded a similar result (Fig. 2, Table 3). The area and production of peas (6 ± 3 fields/year; 25 ± 10 ha/year; 5 ± 0 t/ha) and silage maize (24 ± 4 fields/year; 90 ± 28 ha/year; 12 ± 4 t/ha) did not change, and thus neither did their supply. Growing fava beans on AF1, AF4 and AF5 (3 ± 1 fields/year; 13 ± 6 ha/year) resulted in a total production of 4 ± 0 t/ha, which was not enough to meet the demand for the new animal feed of the LFs over the years.

3.3. A synergistic approach to reach territorial self-sufficiency

To synchronise the annual production of legumes to animal feed requirements from the *complementarity scenario* to the *synergetic scenario*, crop rotations that included peas were modified in 11 fields, for a total of 62 ha. Fava beans were introduced in 27 additional fields (one in AF1, six in AF2, and ten in both AF4 and AF5), for a total of 146 ha. In addition, rotations in six fields of the AFs (45 ha), two fields of LF1 (16 ha) and two fields of LF2 (10 ha) were also changed to balance the supply:demand ratio of maize silage.

By strongly adapting rotations to animal feed requirements, the *synergetic scenario* reached the local self-sufficiency (Fig. 2, Supp. Fig. 4). AFs produced 200 ± 35 t/year of fava bean (AF1, AF2, AF4 ad AF5) and 101 ± 21 t/year of peas (AF3), which completely met the annual feed needs of LF1 and LF2 (58 and 113 t/year, respectively) (Fig. 2). At the territory level, a mean of 51 ± 9 ha of fava beans and 21 ± 4 ha of peas were cropped per year (6 ± 1% and 3 ± 1% of the total UAA, respectively). The small decrease in the average maize silage production (from 1109 ± 504 t/year in the *complementarity scenario* to 978 ± 319 t/year in the *synergetic scenario*) in the new rotations did not influence the self-sufficiency of LFs.

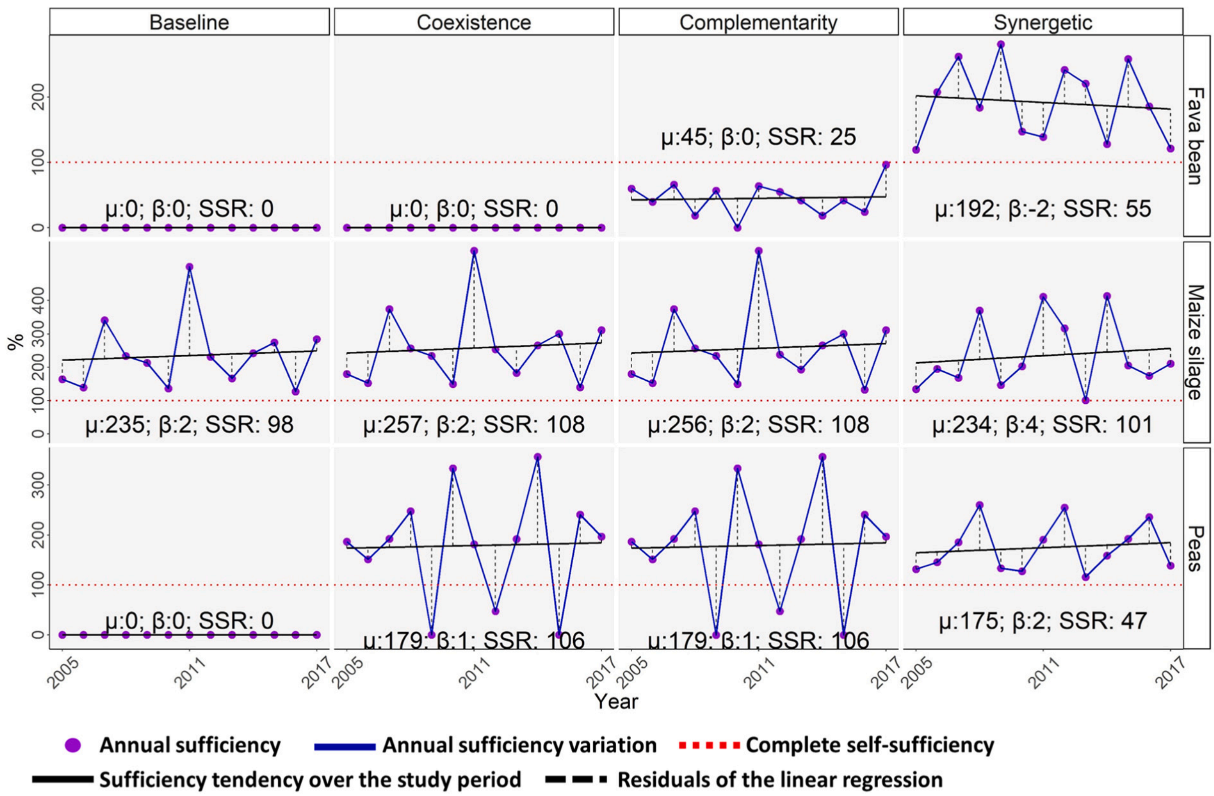

Fig. 2. Self-sufficiency in production over 12 years (2005–2017) for the baseline situation and the coexistence, complementarity and synergetic scenarios for fava bean, peas and maize silage at the territorial level (arable farms + livestock farms). Purple points indicate the annual self-sufficiency for each of crop, solid black lines indicate the production trend over the study period (assessed as a linear regression), vertical dotted black lines indicate residues over the linear regression, and horizontal dotted red lines indicate the production required to feed the cattle of both livestock farmers. Each graph shows the overall mean (μ), slope of the linear regression (β) and sum of squared residues (SSR, an indicator of variability) used to assess the dynamics of each criterion.

Table 3
Annual livestock farm (LF) feed needs (t/year) and self-sufficiency (in %) for each feed ingredient.

Ingredient	LF feed needs (t)		LF self-sufficiency (%)		Territorial self-sufficiency (%)			
	Feed0	Feed1	Feed0	Feed1	Baseline situation	Coexistence scenario	Complementarity scenario	Synergetic scenario
Fodder	158 ± 0	199 ± 0	>500 ± 0	>500 ± 0	>500 ± 0	>500 ± 0	>500 ± 0	472 ± 63
Hay	34 ± 0	115 ± 0	>500 ± 0	>500 ± 0	>500 ± 0	>500 ± 0	>500 ± 0	>500 ± 0
Maize silage	471 ± 0	429 ± 0	235 ± 103	258 ± 113	235 ± 103	258 ± 113	257 ± 113	235 ± 107
Wheat	31 ± 0		>500 ± 0		>500 ± 0			
Cereal grain mix	89 ± 0		79 ± 52		79 ± 52			
Peas		58 ± 0		210 ± 84		210 ± 84	210 ± 84	173 ± 49
Fava bean		103 ± 0					48 ± 23	191 ± 58
Soya bean meal	111 ± 0							
vl3L	89 ± 0	89 ± 0						

Total LF feed needs are shown for the current (Feed0) and new (Feed1) feed formulation. The ability of LFs to be self-sufficient as a function of their own production and the feed formulation (Feed0 or Feed1) is shown in the LF self-sufficiency columns. The ability of the entire territory (i.e. all seven farms) is shown as the supply:demand ratio for the baseline situation (with Feed0) and the three scenarios (with Feed1). vl3L is a feed supplemented for dairy cows. Average ± standard deviation values are shown.

3.4. Performance and vulnerability of TCLS

At the territorial level, trends of most of the performance criteria investigated were similar or improved over the simulation period, while variability (SSR) in the indicators decreased (Fig. 3, Supp. Fig. 5). Only the variability in energy yield increased, albeit not significantly ($P = 0.38$). Over the 13 years simulated, the changes introduced in the *synergetic scenario* did not decrease the average annual energy yield per ha ($P = 0.06$, Supp. Fig. 5a). Conversely, the average annual protein yield increased significantly (by ca. 2%, $P < 0.01$, Supp. Fig. 5b). Economically, gross margin remained constant ($P = 0.06$, Fig. 3a), whereas the economic efficiency of production increased by ca. 3% ($P < 0.01$, Supp. Fig. 5c). As expected, introducing legumes reduced N use significantly by 15 kg N/ha/year (12%; $P < 0.01$, Fig. 3b). However, it also resulted in a small increase of 2% in pesticide applications (+0.08 kg active ingredients per ha), but not a significant one ($P = 0.41$, Supp. Fig. 5d). Average workload decreased by 4% (i.e. ca. 8 min per ha, $P < 0.01$, Fig. 3c). Although workload's overall annual variability did not change, its trend decreased over time. In the *synergetic scenario*, the workload was higher in only three years (2006, 2011 and 2014) than in the baseline situation.

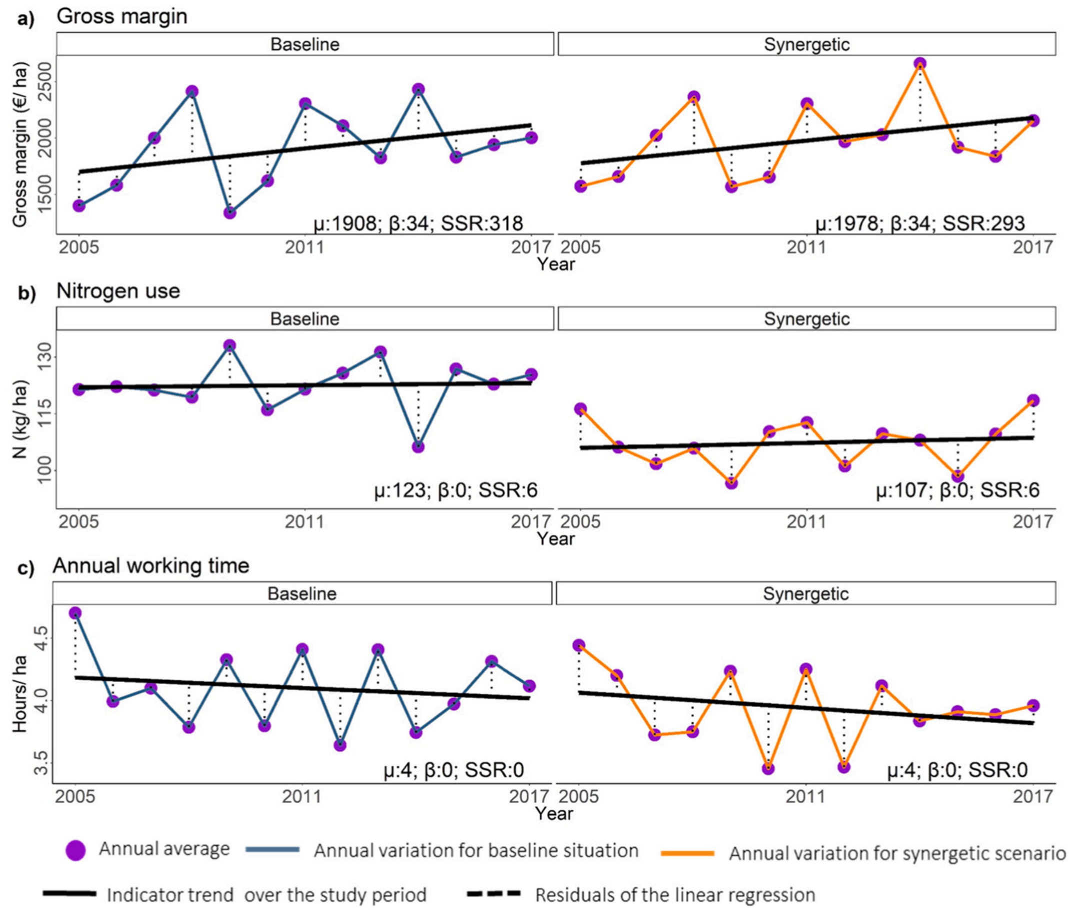

Fig. 3. Dynamics of annual values of three indicators at the territory level in the (left) baseline situation and (right) synergetic scenario: (a) average gross margin (GM), (b) nitrogen (N) use and (c) annual workload. Purple points indicate the annual average value of each indicator, solid black lines indicate the performance trend over the study period (assessed as a linear regression) and vertical dotted black lines indicate residues over the linear regression. Each graph shows the overall mean (μ), slope of the linear regression (β) and sum of squared residues (SSR, an indicator of variability) used to assess the dynamics of each criterion. The mean slope of the nitrogen use indicator (b) differs significantly ($P < 0.01$) between the baseline situation and the synergetic scenario.

3.5. Trade-offs between farm and group performances

Assessing trade-offs among farmers, compared to the *baseline situation*, helped to determine potential economic "losers" and "winners" within the group (Table 4). For the LF group, average annual gross margins increased by 5% (181 €/ha) but differed between the two farmers: LF1's increased by 8% (240 €/ha), whereas LF2's increased by only 3% (122 €/ha) (Table 4). These increases resulted from buying legumes from neighbouring AFs, which reduced the cost of the new feed formulation. As the land use of LFs did not change greatly, the other indicators did not change.

Table 4
Gross margin of vulnerability metrics for the baseline scenario and compared to the synergetic scenario (with respective variation, Δ).

Scale	Baseline situation			Synergetic scenario		
	μ	β	SSR	μ (Δ %)	β (Δ%)	Δ SSR (Δ%)
AF1	1144	36	223	1148 (0%)	36 (−1%)	220 (−1%)
AF2	1073	32	233	1134 (6%)	35 (12%)	272 (17%)
AF3	1821	56	753	1762 (−3%)	53 (−5%)	423 (−44%)
AF4	1036	28	289	1189 (15%)	43 (54%)	276 (−4%)
AF5	1592	68	622	1569 (−1%)	48 (−30%)	473 (−24%)
LF1	2994	−23	498	3232 (8%)	−27 (16%)	710 (43%)
LF2	3693	44	474	3816 (3%)	46 (4%)	561 (18%)
AFs	1333	44	324	1360 (2%)	43 (−2%)	256 (−21%)
LFs	3343	10	458	3524 (5%)	10 (−8%)	592 (29%)
Territory	1908	34	318	1979 (4%)	33 (−2%)	293 (−8%)

The overall mean (μ, given in €/ha), slope of the linear regression (β) and sum of squared residues (SSR) at the individual (for each arable farm (AF) or livestock farm (LF)), group (AFs or LFs) and territory (all farms) levels are shown.

For the AF group, results were mixed. The *synergetic scenario* resulted in an overall higher (by 2%, 27 €/ha) and less variable gross margin (Supp. Table 4a). Hence, in this scenario, the variability in the two economic indicators for the AF group decreased by ca. 21%, and the energy yield decreased by 9%. (Supp. Table 4a). Average energy yield decreased by 6%, but that of protein yield increased by 3% (Supp. Table 4a). The use of N fertiliser and pesticides notably shifted, as expected, with N use decreasing by ca. 21 kg N/ha (16%, $P < 0.01$) and pesticide application increasing by ca. 3% ($P = 0.46$). The longer rotations nearly doubled the annual variability in pesticide application.

At the individual AF level, the gross margins ranged from an average increase of ca. 152 €/ha (AF4) to an average decrease of ca. 60 €/ha (AF3) (Table 4). The results suggest that these contrasting economic performances were related to the crop-rotation changes of each farmer in the *synergetic scenario*. The gross margin of AF1 changed little, as did its crop area (Sup. Fig. 6). For AF3, gross margin decreased significantly by more than 40% in three years (2008, 2012 and 2016) due to higher annual variable costs (Supp. Fig. 6a). In these years, the area cropped with hemp, a highly profitable crop, decreased by ca. 20 ha compared to that in the *baseline situation.* For AF4, fava bean had a positive effect on the annual economic performance (Supp. Fig. 6b). AF3 increased legumes (fava bean) from 0 ha to 22 ± 8 ha per year and decreased maize and cereals by ca. 26% (8 ha) and ca. 20% (7 ha), respectively (Supp.

Fig. 6c). These changes resulted in a 14 ± 14% decrease (−41 ± 41 €/ha) in annual variable costs. The lower annual gross margins of AF3 were due to a decrease in the average hemp area (due to longer rotations) rather than to increased pesticide or fertiliser use (Supp. Table 4a).

Other indicators also differed between AF3 and AF4 (Supp. Fig. 7, Supp. Table 4a). AF3 was the only farm to experience an increase in energy yield (1%) and N use (3 kg N/ha, ca. 3%). Conversely, AF4 experienced an increase in economic efficiency, a decrease in workload (from 5 to 4 h/ha) and a decrease in N use (by 21%, up to 30 kg N/ha). However, its pesticide application increased by 37% (ca. one additional active ingredient per ha). As expected, legumes were the main drivers of the decrease in N use and the ca. 10% decrease in farm energy yield.

Despite the negative mean economic effects, AF3 had the largest decrease in variability for all of the indicators assessed. For this farmer, introducing legumes nearly halved the economic variability, decreased energy yield variability by 76%, and decreased N use variability by 77%. For AF4, variability decreased only for protein yield (by 41%), whereas the variability more than doubled for pesticide application and N use.

4. Discussion

4.1. Synergistic TCLS as a driver of a transition to a self-sufficient and less vulnerable socio-economic and agroecological food system

The literature shows that ICLS can have lower profits at the farm level than specialised farms (e.g. Havet et al., 2014; Ryschawy et al., 2012). Conversely, studies performed at larger scales indicate that promoting TCLS, conceptualised as a social-ecological system (Moraine et al., 2016a), can be a key element in the transition to more efficient and sustainable agricultural systems (Lemaire et al., 2014; Springmann et al., 2018). Our results show that developing exchanges between arable and livestock farmers can open channels for differentiated, profitable and less vulnerable markets (de Roest et al., 2018) and improve certain environmental performances (N use) without significantly worsening others (pesticide application).

In our study, meeting the demand for legumes had a positive influence on socio-economic performance at the territorial level, comprising a reduction in and spreading of typical labour peaks on highly specialised farms (Fig. 3c, Hoagland et al., 2010). As Wilkins (2008) suggested, this can be due to the large decrease in production costs (−8%, ca. -60 €/ha), mainly for N fertiliser (12% reduction) and the use of local plant protein to feed animals, which decreased the total feed cost by ca. 12%. Ryschawy et al. (2018) obtained similar findings for a collective of three arable and four livestock specialised organic farmers. In addition, introducing legumes can also help mitigate climate change, as legumes emit ca. 80% fewer greenhouse gases per unit area than other crops (Jensen et al., 2012) by decreasing inputs of fossil energy (Guardia et al., 2016; Sasu-Boakye et al., 2014). Although we observed a small increase in pesticide use (Supp. Table 4), previous research has shown that diversified crop rotations can reduce pesticide applications (Lechenet et al., 2014) without compromising production (Tamburini et al., 2020). Crop diversification requires efficient calculation procedures, including field experiments that consider effects of the preceding crop and the context of the entire cropping system (Nemecek et al., 2015). Furthermore, the current trend towards landscape specialisation (Verburg et al., 2010) deters arable farmers from diversifying rotations due to the lack of a market for "unconventional" products, such as legumes (Havet et al., 2014). Our results suggest that TCLS based on collaboration between specialised farmers is especially suitable to address situations of uncertainty and reduces economic risks in situations with low crop yields (Herrero et al., 2010).

The changes in the *synergetic scenario* increased the stability of territorial production by reducing the annual variation in legume and maize silage production (by 55% for peas and 6% for maize silage; Fig. 2) and the protein supply (by 57% for peas and 37% maize silage; Supp. Fig. 2). Importantly, no trade-offs between self-sufficiency and vulnerability were observed: performance improved and variability decreased for five of the seven indicators used to assess farm performance (Supp. Table 4a). Thus, a locally organised diversified farming system can be less costly and less vulnerable than a locally independent specialised farming system, which supports the hypothesis of positive effects of economies of scope (de Roest et al., 2018). At the landscape level, a diversified landscape with longer rotations is crucial to minimise losses due to drought, decrease the prevalence of water-demanding crops, such as maize (Passioura and Angus, 2010), and promote biological control (Rusch et al., 2013) and pollination (Catarino et al., 2019b). This is a keystone of new sustainable rural development opportunities (Rivera et al., 2018), as recognised by the OECD (2001), that generate public goods and ecosystem services (de Roest et al., 2018).

4.2. Socio-economic barriers and policy implications

Although the synergistic TCLS (*synergetic scenario*) is an interesting option, its performance depends on how land use and social systems are managed (Garrett et al., 2020). The three crucial obstacles (or "transaction costs") that limit TCLS development include information gathering (new-skill training, market exploration and potential partners), collective decision-making (spatial and temporal planning and land-use coordination) and operational monitoring (see a detailed analysis in Asai et al., 2018). As shown in our study, these organisational challenges arise because a TCLS involves strategic organisation among farmers that must consider trade-offs between individual and collective objectives (Ryschawy et al., 2017) and performances (Table 4). For example, while the gross margin of AF4 increased by 152 €/ha, and its annual variability decreased by nearly 5%, the gross margin of AF3 decreased by ca. 60 €/ha. Both results were directly related to the land use in space and time, and thus to the associated variable costs. In our study, the *synergetic scenario* implied that AFs would convert ca. 5 ± 3% (i.e. 16 ± 8 ha) of their UAA to legumes per year. This non-negligible area has major implications for equipment purchases, the infrastructure required and the understanding of legume crop management and agronomy.

Although it lay beyond the scope of this study, further interactions with and between farmers would help to identify adaptations of land use that would equalise benefits among farmers. Regardless of the results of these interactions, highlighting possible winners and losers would enable farmers to consider unequal results among themselves explicitly and to weigh the advantages and disadvantages of the TCLS envisioned. It may also help them to define suitable contracts and potential opportunities to share resources. The support of local farmer cooperatives and expert advisory bodies (e.g. the Chamber of Agriculture) can help to develop and strengthen the social structure required within the local farming community (Garrett et al., 2020) and to value the farmers' willingness to change their current practices and engage in direct exchanges. However, agricultural production chains and public policy, such as the European Union's Common Agricultural Policy (CAP), strongly influence which crops farmers choose to grow. Thus, to encourage the introduction and continuity of TCLS, we recommend including three specific measures in agriculture policies, such as the new CAP framework for 2021–2027:

- Develop dedicated institutional support for direct bilateral or multilateral contracts or payment arrangements based on direct exchanges between farmers.
- Include specific financial and technical support, such as subsidies to purchase specific equipment (e.g. legume storage and processing infrastructure) when new contracts are drawn up.
- Establish a specific premium for products from TCLS. It would encourage market differentiation, such as that for organic farming, as consumer expectations for products and production methods also have substantial effects (McFadden and Huffman, 2017).

4.3. Strengths, weaknesses and replicability of the approach

As Martin et al. (2016) suggested, we used a spatial and dynamic modelling platform as a decision support system to perform IAM of TCLS scenarios. Compared to classic approaches based on static assessment, it provides detailed dynamic simulation of multilevel effects of interactions among individual strategies and the key spatial and/or temporal variabilities (Dardonville et al., 2020): soil, climate, prices, crop patterns and rotations. Our IAM approach dynamically examined performances, vulnerabilities and drivers behind the distinct individual results (Supp. Fig. 7). This provides transparent and precise multilevel and multicriteria information about the variation in performances over time. The approach is based on integrating and hybridising multiple sources of generic and local information (Murgue et al., 2016). It includes creating an explicit fine-scale representation of a real agricultural landscape with multiple biophysical characteristics (e.g. soil and weather), populated with actual farmers with heterogeneous behaviour (in practices and objectives).

However, we acknowledge three major limitations. First, we restricted our analysis to cash crop management, thus ignoring the behaviour and dynamics of grasslands and livestock. Future modelling should include the livestock production cycle, including the changing needs of dairy cows throughout the year, annual dynamics of forage supply/demand and animal waste production. These aspects would capture intra- and inter-annual dynamics of demand for feedstock (protein and energy-based) and highlight the need to import protein supplements to buffer a potential temporary deficit. Second, at the crop level, the N cycle in the soil and its influence on plant development and N emissions were not considered. In addition, pest damage and the abatement effects of pesticides were not considered, as few models of them exist (but see Catarino et al. (2019a, 2016)). Third, future studies should include other relevant environmental indicators (e.g. greenhouse gas emissions), along with economic and climate assessments. However, as an ongoing project, MAELIA is addressing these limitations in order to provide more realistic results.

Due to the relatively small territory studied, the conclusions are context-dependent and thus may have little influence on understanding potential TCLS at regional or national levels. However, provided that farmers are willing to synergistically cooperate, and key policies are put in place, the results should stand elsewhere. Yet, we recommend that this case study be replicated with different social contexts. The IAM methodology has a relevant generic and reproducible character and can be applied and expanded to other and larger territories. For Europe, key data can be obtained from national or European databases. Maps of crop rotations can be obtained from the LPIS (Levavasseur et al., 2016; Zimmermann et al., 2016), climate data can be extracted from the *E*-OBS dataset (Copernicus ECMWF, 2019), and soil data can be obtained from the European Soil Data Centre (European Soil Data Centre, 2019). For larger territories (e.g. administrative departments), crop (and livestock) management-decision rules will need to be generalised (e.g. for each crop within a specific cropping system) and not consider specific farmer characteristics (Murgue et al., 2014), as the present study did. Therefore, individual details are lost (e.g. crop sequences, technical operations), but broader contextualisation is gained (e.g. feasibility of economic gains at a larger scale). Simulation processing time is not a limitation, but in the present study, the time required to collect data (ca. one month), format it (ca. one month) and calibrate simulations (three months, including implementation) was not negligible.

5. Conclusion

Despite the predictable benefits of bringing together specialist crop and livestock farms, the current trend is for a decrease in TCLS. Currently, the lack of dedicated tools limits the ability to support iterative design and assessment of TCLS that involves stakeholders. By using the MAELIA platform, we developed and applied for the first time a dynamic spatially explicit IAM approach that supports crop-livestock integration at the territorial level (here, a collective of farmers). We show that MAELIA is adapted to support the necessary design and assessment by simulating dynamic interactions among technical operations, soil and climate conditions, and crop growth to assess self-sufficiency, sustainability (via environmental and socio-economic performances) and vulnerabilities, including trade-offs and synergies between individual and group objectives.

The results of our study show that diversification through the development of legume exchanges between arable and livestock farmers, supported by close cooperation, can create the potential for economies of scope to decrease the vulnerability of farming systems while improving their sustainability. In addition, no major trade-offs between self-sufficiency and vulnerability were observed. Therefore, we highlight that TCLS can effectively contribute to an environmentally sustainable and economically viable agroecological transition. However, it may require adapted policies and local analyses and support for the development of TCLS.

Our study included a collective of seven farmers, but local dissemination by the participants involved could encourage others in the vicinity to join the collective and redesign their farming systems. In such a new locally collaborative mode of organisation, farmers' production is no longer driven only by global market signals but also influenced by the location of the farm and what neighbouring farmers need and produce. Given our results and the motivation of the farmers towards TCLS, we recommend that local agriculture advisory bodies (e.g. CRAPL) encourage the development of strong collaboration within this collective of farmers. In addition, future studies should address the sensitivity of TLCS on the impact of climatic and economic variability in the territory.

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Declaration of Competing Interest

The authors declare no conflict of interest.

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Appendix A. Supplementary data

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References

Allain, S., Ndong, G.O., Lardy, R., Leenhardt, D., 2018. Integrated assessment of four strategies for solving water imbalance in an agricultural landscape. Agron. Sustain. Dev. 38 https://doi.org/10.1007/s13593-018-0529-z.

Asai, M., Langer, V., Frederiksen, P., Jacobsen, B.H., 2014. Livestock farmer perceptions of successful collaborative arrangements for manure exchange: a study in Denmark. Agric. Syst. 128, 55–65. https://doi.org/10.1016/j.agsy.2014.03.007.

Asai, M., Moraine, M., Ryschawy, J., de Wit, J., Hoshide, A.K., Martin, G., 2018. Critical factors for crop-livestock integration beyond the farm level: a cross-analysis of worldwide case studies. Land Use Policy 73, 184–194. https://doi.org/10.1016/j.landusepol.2017.12.010.

Barnosky, A.D., Hadly, E.A., Bascompte, J., Berlow, E.L., Brown, J.H., Fortelius, M., Getz, W.M., Harte, J., Hastings, A., Marquet, P.A., others, 2012. Approaching a state

shift in Earth's biosphere. Nature 486, 52–58. https://doi.org/10.1038/nature11018.
Bell, L.W., Moore, A.D., Kirkegaard, J.A., 2014. Evolution in crop–livestock integration systems that improve farm productivity and environmental performance in Australia. Eur. J. Agron. 57, 10–20. https://doi.org/10.1016/j.eja.2013.04.007.
Catarino, R., Ceddia, G., Areal, F., Parisey, N., Park, J., 2016. Managing maize under pest species competition: is Bt (bacillus thuringiensis) maize the solution? Ecosphere 7. https://doi.org/10.1002/ecs2.1340.
Catarino, R., Areal, F., Park, J., Parisey, N., 2019a. Spatially explicit economic effects of non-susceptible pests' invasion on Bt maize. Agric. Syst. 175, 22–33. https://doi.org/10.1016/j.agsy.2019.05.008.
Catarino, R., Bretagnolle, V., Perrot, T., Vialloux, F., Gaba, S., 2019b. Bee pollination outperforms pesticides for oilseed crop production and profitability. Proc. R. Soc. B Biol. Sci. 286, 20191550. https://doi.org/10.1098/rspb.2019.1550.
Chambagri, 2019. Panorama socio-économique de l'agriculture des Pays de la Loire. Données régionales et spécificités départementales: Chiffres 2017. ANGERS.
Constantin, J., Willaume, M., Murgue, C., Lacroix, B., Therond, O., 2015. The soil-crop models STICS and AqYield predict yield and soil water content for irrigated crops equally well with limited data. Agric. For. Meteorol. 206, 55–68. https://doi.org/10.1016/j.agrformet.2015.02.011.
Copernicus ECMWF, 2019. The Copernicus Climate Change Service (C3S) - Monitoring European Climate Using Surface Observations (European Union).
Dainese, M., Martin, E.A., Aizen, M.A., Albrecht, M., Bartomeus, I., Bommarco, R., Carvalheiro, L.G., Chaplin-Kramer, R., Gagic, V., Garibaldi, L.A., Ghazoul, J., Grab, H., Jonsson, M., Karp, D.S., Kennedy, C.M., Kleijn, D., Kremen, C., Landis, D. A., Letourneau, D.K., Marini, L., Poveda, K., Rader, R., Smith, H.G., Tscharntke, T., Andersson, G.K.S., Badenhausser, I., Baensch, S., Bezerra, A.D.M., Bianchi, F.J.J.A., Boreux, V., Bretagnolle, V., Caballero-Lopez, B., Cavigliasso, P., Ćetković, A., Chacoff, N.P., Classen, A., Cusser, S., da Silva e Silva, F.D., de Groot, G.A., Dudenhöffer, J.H., Ekroos, J., Fijen, T., Franck, P., Freitas, B.M., Garratt, M.P.D., Gratton, C., Hipólito, J., Holzschuh, A., Hunt, L., Iverson, A.L., Jha, S., Keasar, T., Kim, T.N., Kishinevsky, M., Klatt, B.K., Klein, A.-M., Krewenka, K.M., Krishnan, S., Larsen, A.E., Lavigne, C., Liere, H., Maas, B., Mallinger, R.E., Martinez Pachon, E., Martínez-Salinas, A., Meehan, T.D., Mitchell, M.G.E., Molina, G.A.R., Nesper, M., Nilsson, L.O., Rourke, M.E., Peters, M.K., Plećaš, M., Potts, S.G., de Ramos, D.L., Rosenheim, J.A., Rundlöf, M., Rusch, A., Sáez, A., Scheper, J., Schleuning, M., Schmack, J.M., Sciligo, A.R., Seymour, C., Stanley, D.A., Stewart, R., Stout, J.C., Sutter, L., Takada, M.B., Taki, H., Tamburini, G., Tschumi, M., Viana, B.F., Westphal, C., Willcox, B.K., Wratten, S.D., Yoshioka, A., Zaragoza-Trello, C., Zhang, W., Zou, Y., Steffan-Dewenter, I., 2019. A global synthesis reveals biodiversity-mediated benefits for crop production. Sci. Adv. 5, eaax0121 https://doi.org/10.1126/sciadv.aax0121.
Dardonville, M., Urruty, N., Bockstaller, C., Therond, O., 2020. Influence of diversity and intensification level on vulnerability, resilience and robustness of agricultural systems. Agric. Syst. 184, 102913. https://doi.org/10.1016/j.agsy.2020.102913.
de Roest, K., Ferrari, P., Knickel, K., 2018. Specialisation and economies of scale or diversification and economies of scope? Assessing different agricultural development pathways. J. Rural. Stud. 59, 222–231. https://doi.org/10.1016/j.jrurstud.2017.04.013.
European Soil Data Centre, 2019. European Soil Database (distribution version V2.0). European Commission, Joint Research Centre, Luxembourg.
Eurostat, 2018. Agriculture forestry and fishery statistics. Eur. Union. https://doi.org/10.2785/340432.
Fernandez-Mena, H., Gaudou, B., Pellerin, S., MacDonald, G.K., Nesme, T., 2020a. Flows in agro-food networks (FAN): an agent-based model to simulate local agricultural material flows. Agric. Syst. 180, 102718. https://doi.org/10.1016/j.agsy.2019.102718.
Fernandez-Mena, H., MacDonald, G.K., Pellerin, S., Nesme, T., April 2020. Co-benefits and Trade-Offs from agro-food system redesign for circularity: a case study with the FAN Agent-based model. Front. Sustain. Food Syst. 180, 102718.
Garrett, R.D., Ryschawy, J., Bell, L.W., Cortner, O., Ferreira, J.N., Garik, A.V.N., Gil, J.D. B., Klerkx, L., Moraine, M., Peterson, C.A., dos Reis, J.C., Valentim, J.F., 2020. Drivers of decoupling and recoupling of crop and livestock systems at farm and territorial scales. Ecol. Soc. 15, 24. https://doi.org/10.5751/ES-11412-250124.
Grandgirard, D., Zielinski, R., 2008. Land Parcel Identification System (LPIS) Anomalies' Sampling and Spatial Pattern. JRC Sci. Tech. Reports.
Guardia, G., Tellez-Rio, A., García-Marco, S., Martin-Lammerding, D., Tenorio, J.L., Ibáñez, M.Á., Vallejo, A., 2016. Effect of tillage and crop (cereal versus legume) on greenhouse gas emissions and global warming potential in a non-irrigated Mediterranean field. Agric. Ecosyst. Environ. 221, 187–197. https://doi.org/10.1016/j.agee.2016.01.047.
Havet, A., Coquil, X., Fiorelli, J.L., Gibon, A., Martel, G., Roche, B., Ryschawy, J., Schaller, N., Dedieu, B., 2014. Review of livestock farmer adaptations to increase forages in crop rotations in western France. Agric. Ecosyst. Environ. 190, 120–127. https://doi.org/10.1016/j.agee.2014.01.009.
Herrero, M., Thornton, P.K., Notenbaert, A.M., Wood, S., Msangi, S., Freeman, H.A., Bossio, D., Dixon, J., Peters, M., van de Steeg, J., Lynam, J., Rao, P.P., Macmillan, S., Gerard, B., McDermott, J., Seré, C., Rosegrant, M., 2010. Smart investments in sustainable food production: revisiting mixed crop-livestock systems. Science (80-.) 327, 822–825.
Hoagland, L., Hodges, L., Helmers, G.A., Brandle, J.R., Francis, C.A., 2010. Labor availability in an integrated agricultural system. J. Sustain. Agric. 34, 532–548.
Hossard, L., Guichard, L., Pelosi, C., Makowski, D., 2017. Lack of evidence for a decrease in synthetic pesticide use on the main arable crops in France. Sci. Total Environ. 575, 152–161. https://doi.org/10.1016/j.scitotenv.2016.10.008.
IGN-Institut National de l''Information Géographique et Forestière, 2018. Registre parcellaire graphique (RPG) : contours des parcelles et îlots culturaux et leur groupe de cultures majoritaire [WWW Document].
INSEE, 2020. Monthly agricultural producer price indices - general index. In: Agricultural price indices [WWW Document]. Main indices time Ser. https://www.insee.fr/fr/statistiques/3735079 (accessed 4.1.20).
Jensen, E.S., Peoples, M.B., Boddey, R.M., Gresshoff, P.M., Hauggaard-Nielsen, H., Alves, J.R.B., Morrison, M.J., 2012. Legumes for mitigation of climate change and the provision of feedstock for biofuels and biorefineries. A review. Agron. Sustain. Dev. 32, 329–364. https://doi.org/10.1007/s13593-011-0056-7.
Jouan, J., Ridier, A., Carof, M., 2020. SYNERGY: a regional bio-economic model analyzing farm-to-farm exchanges and legume production to enhance agricultural sustainability. Ecol. Econ. 175, 106688. https://doi.org/10.1016/j.ecolecon.2020.106688.
Lardy, R., Mazzega, P., Sibertin-Blanc, C., Auda, Y., Sanchez-Perez, J.-M., Sauvage, S., Therond, O., 2014. Calibration of simulation platforms including highly interweaved processes: the MAELIA multi-agent platform. In: Proceedings of the 7th International Congress on Environmental Modelling and Software, June, pp. 15–19.
Lebacq, T., Baret, P.V., Stilmant, D., 2015. Role of input self-sufficiency in the economic and environmental sustainability of specialised dairy farms. Animal 9, 544–552. https://doi.org/10.1017/S1751731114002845.
Lechenet, M., Bretagnolle, V., Bockstaller, C., Boissinot, F., Petit, M.-S., Petit, S., Munier-Jolain, N.M., 2014. Reconciling pesticide reduction with economic and environmental sustainability in arable farming. PLoS One 9, e97922.
Lemaire, G., Franzluebbers, A., de Carvalho, P.C.F., Dedieu, B., 2014. Integrated crop–livestock systems: Strategies to achieve synergy between agricultural production and environmental quality. Agric. Ecosyst. Environ. 190, 4–8. https://doi.org/10.1016/j.agee.2013.08.009.
Levavasseur, F., Martin, P., Bouty, C., Barbottin, A., Bretagnolle, V., Thérond, O., Scheurer, O., Piskiewicz, N., 2016. RPG explorer: a new tool to ease the analysis of agricultural landscape dynamics with the land parcel identification system. Comput. Electron. Agric. 127, 541–552. https://doi.org/10.1016/j.compag.2016.07.015.
Martin, G., Moraine, M., Ryschawy, J., Magne, M.-A., Asai, M., Sarthou, J.-P., Duru, M., Therond, O., 2016. Crop–livestock integration beyond the farm level: a review. Agron. Sustain. Dev. 36, 53. https://doi.org/10.1007/s13593-016-0390-x.
Martin, G., Magne, M.-A., Cristobal, M.S., 2017. An integrated method to analyze farm vulnerability to climatic and economic variability according to farm configurations and Farmers' adaptations. Front. Plant Sci. 8, 1483. https://doi.org/10.3389/fpls.2017.01483.
Mazzega, P., Therond, O., Debril, T., March, H., Sibertin-Blanc, C., Lardy, R., Sant'ana, D., 2014. Critical multi-level governance issues of integrated modelling: an example of low-water management in the adour-garonne basin (France). J. Hydrol. 519, 2515–2526. https://doi.org/10.1016/j.jhydrol.2014.09.043.
McFadden, J.R., Huffman, W.E., 2017. Willingness-to-pay for natural, organic, and conventional foods: the effects of information and meaningful labels. Food Policy 68, 214–232. https://doi.org/10.1016/j.foodpol.2017.02.007.
McGranahan, D.A., 2014. Ecologies of scale: multifunctionality connects conservation and agriculture across fields, farms, and landscapes. Land. https://doi.org/10.3390/land3030739.
Moraine, M., Duru, M., Therond, O., 2016a. A social-ecological framework for analyzing and designing integrated crop–livestock systems from farm to territory levels. Renew. Agric. Food Syst. 32, 43–56. https://doi.org/10.1017/S1742170515000526.
Moraine, M., Grimaldi, J., Murgue, C., Duru, M., Therond, O., 2016b. Co-design and assessment of cropping systems for developing crop-livestock integration at the territory level. Agric. Syst. 147, 87–97. https://doi.org/10.1016/j.agsy.2016.06.002.
Moraine, M., Melac, P., Ryschawy, J., Duru, M., Therond, O., 2017. A participatory method for the design and integrated assessment of crop-livestock systems in farmers' groups. Ecol. Indic. 72, 340–351. https://doi.org/10.1016/j.ecolind.2016.08.012.
Murgue, C., Lardy, R., Vavasseur, M., Burger-Leenhardt, D., Therond, O., 2014. Fine spatio-temporal simulation of cropping and farming systems effects on irrigation withdrawal dynamics within a river basin. In: Ames, D.P., Quinn, N.W.T., Rizzoli, A. E. (Eds.), Proceedings of the 7th International Congress on Environmental Modelling and Software (IEMSs). 2014; 7. International Congress on Environmental Modelling and Software, Santiago, USA, 2014-06-15-2014-06-19,. International Environmental Modelling and Software Society (iEMSs).
Murgue, C., Therond, O., Leenhardt, D., 2015. Toward integrated water and agricultural land management: participatory design of agricultural landscapes. Land Use Policy 45, 52–63. https://doi.org/10.1016/j.landusepol.2015.01.011.
Murgue, C., Therond, O., Leenhardt, D., 2016. Hybridizing local and generic information to model cropping system spatial distribution in an agricultural landscape. Land Use Policy 54, 339–354. https://doi.org/10.1016/j.landusepol.2016.02.020.
Nemecek, T., Hayer, F., Bonnin, E., Carrouée, B., Schneider, A., Vivier, C., 2015. Designing eco-efficient crop rotations using life cycle assessment of crop combinations. Eur. J. Agron. 65, 40–51. https://doi.org/10.1016/j.eja.2015.01.005.
OECD, 2001. Multifunctionality: Towards an Analytical Framework. Paris. https://doi.org/10.1787/9789264192171-en.
Panagos, P., Van Liedekerke, M., Jones, A., Montanarella, L., 2012. European soil data Centre: response to European policy support and public data requirements. Land Use Policy 29, 329–338. https://doi.org/10.1016/j.landusepol.2011.07.003.
Passioura, J.B., Angus, J.F., 2010. Chapter 2 - Improving productivity of crops in water-limited environments. In: Sparks, D.L.B.T.-A. in A (Ed.), Advances in Agronomy V106. Academic Press, pp. 37–75. https://doi.org/10.1016/S0065-2113(10)06002-5.

Peyraud, J., Taboada, M., Delaby, L., 2014. Integrated crop and livestock systems in Western Europe and South America: a review. Eur. J. Agron. 57, 31–42. https://doi.org/10.1016/j.eja.2014.02.005.

Regan, J.T., Marton, S., Barrantes, O., Ruane, E., Hanegraaf, M., Berland, J., Korevaar, H., Pellerin, S., Nesme, T., 2017. Does the recoupling of dairy and crop production via cooperation between farms generate environmental benefits? A case-study approach in Europe. Eur. J. Agron. 82, 342–356. https://doi.org/10.1016/j.eja.2016.08.005.

Rivera, M., Knickel, K., de los Rios, I., Ashkenazy, A., Pears, D.Q., Chebach, T., Šūmane, S., 2018. Rethinking the connections between agricultural change and rural prosperity: A discussion of insights derived from case studies in seven countries. J. Rural. Stud. 59, 242–251. https://doi.org/10.1016/j.jrurstud.2017.07.006.

Rizzo, D., Therond, O., Lardy, R., Murgue, C., Leenhardt, D., 2019. A rapid, spatially explicit approach to describe cropping systems dynamics at the regional scale. Agric. Syst. 173, 491–503. https://doi.org/10.1016/j.agsy.2019.04.003.

Rusch, A., Bommarco, R., Jonsson, M., Smith, H.G., Ekbom, B., 2013. Flow and stability of natural pest control services depend on complexity and crop rotation at the landscape scale. J. Appl. Ecol. 50, 345–354. https://doi.org/10.1111/1365-2664.12055.

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

Ryschawy, J., Choisis, N., Choisis, J.P., Gibon, A., 2013. Paths to last in mixed crop–livestock farming: lessons from an assessment of farm trajectories of change. Animal 7, 673–681. https://doi.org/10.1017/S1751731112002091.

Ryschawy, J., Martin, G., Moraine, M., Duru, M., Therond, O., 2017. Designing crop–livestock integration at different levels: toward new agroecological models? Nutr. Cycl. Agroecosyst. 108, 5–20. https://doi.org/10.1007/s10705-016-9815-9.

Ryschawy, J., Moraine, M., Péquignot, M., Martin, G., 2018. Trade-offs among individual and collective performances related to crop–livestock integration among farms: a case study in southwestern France. Org. Agric. https://doi.org/10.1007/s13165-018-0237-7.

Sasu-Boakye, Y., Cederberg, C., Wirsenius, S., 2014. Localising livestock protein feed production and the impact on land use and greenhouse gas emissions. Animal 8, 1339–1348. https://doi.org/10.1017/S1751731114001293.

Springmann, M., Clark, M., Mason-D'Croz, D., Wiebe, K., Bodirsky, B.L., Lassaletta, L., de Vries, W., Vermeulen, S.J., Herrero, M., Carlson, K.M., Jonell, M., Troell, M., DeClerck, F., Gordon, L.J., Zurayk, R., Scarborough, P., Rayner, M., Loken, B., Fanzo, J., Godfray, H.C.J., Tilman, D., Rockström, J., Willett, W., 2018. Options for keeping the food system within environmental limits. Nature 562, 519–525. https://doi.org/10.1038/s41586-018-0594-0.

Tamburini, G., Bommarco, R., Wanger, T.C., Kremen, C., van der Heijden, M.G.A., Liebman, M., Hallin, S., 2020. Agricultural diversification promotes multiple ecosystem services without compromising yield. Sci. Adv. 6, eaba1715 https://doi.org/10.1126/sciadv.aba1715.

Therond, O., Hengsdijk, H., Casellas, E., Wallach, D., Adam, M., Belhouchette, H., Oomen, R., Russell, G., Ewert, F., Bergez, J.-E., Janssen, S., Wery, J., Van Ittersum, M.K., 2011. Using a cropping system model at regional scale: low-data approaches for crop management information and model calibration. Agric. Ecosyst. Environ. 142, 85–94. https://doi.org/10.1016/j.agee.2010.05.007.

Therond, O., Sibertin-Blanc, C., Lardy, R., Gaudou, B., Balestrat, M., Hong, Y., Louail, T., Panzoli, D., Sanchez-Perez, J.-M., Sauvage, S., 2014. Integrated modelling of social-ecological systems: The MAELIA high-resolution multi-agent platform to deal with water scarcity problems. In: Ames, D., Quinn, N., Rizzoli, A. (Eds.), International Environmental Modelling and Software Society (IEMSs); 7th Intl. Congress on Env. Modelling and Software, San Diego, CA, USA. San Diego, CA, USA.

Tribouillois, H., Constantin, J., Guillon, B., Willaume, M., Aubrion, G., Fontaine, A., Hauprich, P., Kerveillant, P., Laurent, F., Therond, O., 2020. AqYield-N: a simple model to predict nitrogen leaching from crop fields. Agric. For. Meteorol. 284, 107890. https://doi.org/10.1016/j.agrformet.2019.107890.

Verburg, P.H., van Berkel, D.B., van Doorn, A.M., van Eupen, M., van den Heiligenberg, H.A.R.M., 2010. Trajectories of land use change in Europe: a model-based exploration of rural futures. Landsc. Ecol. 25, 217–232. https://doi.org/10.1007/s10980-009-9347-7.

Vérité, R., Peyraud, J.L., 1988. Nutrition azotée. In: Alimentation Des Bovins, Ovins et Caprins. Inst. Natl. Rech. Agron, Paris, pp. 75–93.

Vidal, J.-P., Martin, E., Franchistéguy, L., Baillon, M., Soubeyroux, J.-M., 2010. A 50-year high-resolution atmospheric reanalysis over France with the Safran system. Int. J. Climatol. 30, 1627–1644. https://doi.org/10.1002/joc.2003.

Villalobos, F., Testi, L., Mateos, L., Fereres, E., 2016. The energy balance. In: Villalobos, F.J., Fereres, Elias (Eds.), Principles of Agronomy for Sustainable Agriculture. Springer.

Weindl, I., Lotze-Campen, H., Popp, A., Müller, C., Havlík, P., Herrero, M., Schmitz, C., Rolinski, S., 2015. Livestock in a changing climate: production system transitions as an adaptation strategy for agriculture. Environ. Res. Lett. 10, 94021. https://doi.org/10.1088/1748-9326/10/9/094021.

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

Zimmermann, J., González, A., Jones, M.B., O'Brien, P., Stout, J.C., Green, S., 2016. Assessing land-use history for reporting on cropland dynamics—a comparison between the land-parcel identification system and traditional inter-annual approaches. Land Use Policy 52, 30–40. https://doi.org/10.1016/j.landusepol.2015.11.027.