A model to explore which diversity is needed to design sustainable agricultural systems at the territorial level

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RESEARCH ARTICLE

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Abstract

Faced with changes related to climatic hazards or market variability, farmers deploy a variety of strategies to stabilize farm economic performances and reduce risk. One of the challenges faced by agricultural systems is how to reduce their sensitivity to these disturbances and maintain a certain level of production of goods and services. If diversity in crop and livestock activities in a farm has been shown to answer this challenge, at a higher scale, the growth of diversity and its benefits remain unclear. Using biotechnical models of existing farms within the territory of the Vallées de Duyes in the South of France, we propose to simulate various territorial configurations based on the assumption of diversity at farm and territorial scales and assess their expected sustainable properties. Based on the actual configuration of the referenced territory and composed of a set of specialized and mixed farms, two contrasted configurations are tested: from one side, a territory composed of specialized farms and, from the other side, a territory composed of mixed farms. The intrinsic diversity of individual farms impacts their performance and reveals that the resistance to economic shock varies according to the dependence on inputs and the use of rangelands. If mixed farms exhibit high values of diversity indicators for both land use and product provision, they also present high values for the majority of sustainable properties. At a higher scale, the specialized configuration shows the highest resistance to economic shock, but economic performances are lower than the referenced and specialized configurations. Here, we explore for the first time how several types of diversity indicators, both built within and between farms, could affect a set of sustainable properties of farms and territories. These new insights lead to a better understanding of how to balance performance at several scales and design sustainable Mediterranean farming systems.

Keywords Crop-livestock activities · Farming systems · Territory performances · Pastoral systems · Sustainability assessment · Mediterranean · Simulation

1 Introduction

Farming systems, and the territories in which they are located, are facing increasing recurring and brutal changes (Altieri et al. 2015). These changes originate from various sources (climatic, economic, etc.) and affect farming systems differently according to their sensitivity. Sensitivity is understood as "the degree to which the system is modified or affected by an internal or external disturbance" (Gallopin 2006). One of the challenges faced by

agricultural systems is how to reduce their sensitivity to these disturbances and maintain a certain level of production of goods and services (Darnhofer et al. 2010).

To reduce the sensitivity of agricultural systems, the need to increase diversity (Anderies et al. 2013; Lin 2011; Stark et al. 2016) is the consensus in scientific literature (Duru et al. 2015). Diversity is built at different scales (Martin and Magne 2015) and provides various benefits according to activated ecological and biological processes (Bonaudo et al. 2014; Gaba et al. 2015).

Integrated crop-livestock systems are an archetype of diversified farming systems that mobilize ecological interactions between system components (e.g., crops, grasslands, and animals). These interactions allow synergistic nutrients to cycle between them, contributing to their global performances as resource use efficiency, resilience, or self-sufficiency (Hendrickson et al. 2008; Kremen et al. 2012;

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Ryschawy et al. 2014). Stark et al. (2018) compare the agro-ecological performances of contrasted mixed farming systems in Latino-Caribbean territories and show that integration based on the diversity of farming components is effective in promoting resilience in the face of possible disturbances, according to the diversity of flows connecting these components. The relevance of combining two productive activities in a farming system to improve its resilience has been demonstrated (Lawes and Kindwell 2012; Pacin and Oesterheld 2014; Ripoll-Bosch et al. 2014). Indeed, when one activity faces disturbances, another activity could remain unaffected.

Nevertheless, the impact of the combination of crop and livestock activities to maintain a set of performance values under disturbances, such as weather or economic shocks, remains a topic underexplored at the territory scale. Even if evidence supporting the hypothesis of the benefits of using diversity to face uncertainty is strong at field-scale, herd-scale (Tichit et al. 2011; Tilman et al. 2006), and at farm-scale (Funes-monzote et al. 2009; Tengo and Belfrage 2004) levels, the building of diversity and its benefits remain unclear at higher scales. As crop-livestock farms are theoretically optimized to improve the sustainability of agriculture, authors argue that crop-livestock integration may be organized beyond the farm level (Martin et al. 2016). At the territory scale, the coexistence of diversity within farming systems (with their potential interactions) has recently been investigated in order to design more sustainable agricultural systems. Authors have tried to explain the drivers of crop-livestock integration at the territorial scale (Asai et al. 2018; Garrett et al. 2020), conceptualize the possible configurations of crop-livestock systems at the territorial scale (Moraine et al. 2016), or assess the trade-off among individual and collective performances related to crop-livestock integration (Ryschawy et al. 2014).

Based on the literature, we make the assumptions that designing diversified agricultural territories is relevant to reduce the sensitivity of agricultural systems, according to how diversity is built. Indeed, a remaining question is relative to the intrinsic diversity of each farming system and to the proportion of more or less diversified farms composing the territory. Therefore, the ability to cope with disturbances and to provide services and benefits would be affected by diversity built at territory scale.

To answer this question, we base our study on a territory in the South of France that is relevant to treating this problem of improving diversity to face changes and disturbances. Using biotechnical models of existing farms within the territory, we propose to simulate various territorial configurations based on the assumption of diversity at farm and territorial scales and to assess expected sustainable properties.

To design more sustainable systems, it is important to compare different modalities, according to the assumptions made, and to evaluate them. To do so, the behavior of different systems, including new systems, faced with various changing situations must be explored. Simulation and ex ante assessment are relevant experiments to explore innovations and to codesign solutions for the future.

2 Material and methods

2.1 Case study: the Vallée des Duyes

In Provence-Alpes-Côtes-d'Azur (PACA), in Southern France (Fig. 1), the abandonment of livestock activities led to an orientation of the farming system toward a specialization in cropping systems, such as hard wheat or aromatic and medicinal plants (i.e., lavender or lavandin). The decrease in the livestock population implies a modification in land use, especially for rangelands. Abandoning grazing would "close off" the environment. It results in its impoverishment and hence a long-term decline in biodiversity (Lepart et al. 2011). However, several types of specialized and mixed farming systems remain in this territory. While interactions between crop and livestock activities within the farm are inherent to the functioning of mixed farms (organic fertilization, crop for animal diet), very few interactions currently take place between farms.

New alternatives of organization between crop and livestock interactions have emerged over the last decade, such as orchard or veneer grazing (Cerpam 2017) or winter transhumance. However, Mediterranean farming systems are relatively constrained systems because they are strongly dependent on climatic conditions influencing the availability of resources in pastures and rangelands. They are also affected by the hazards of the markets. Ripoll-Bosch et al. (2014) noted that in sheep farms in less favored areas in Southern Europe, the diversity of the production mix enhances farm flexibility and can be a strategy for handling uncertainty that does not necessarily improve labor profitability. The alternatives of organization between crop and livestock interactions can lead to changes in land use. Their changes modify product provisions by agricultural activities and thus the sustainability of agricultural systems. Before promoting these types of alternatives and their modes of implementation, it is important to assess their performance in terms of sustainability, such as their ability to cope with disturbance and service provision.

The study area is the Vallée des Duyes, a valley of the Alpes de Haute Provence in Provence-Alpes-Côtes-d'Azur. The Vallée des Duyes stretches approximately 20 km from north to south.

For study purposes, we have divided the territory into four areas according to their land use conditions and their main agricultural orientations:

- In the south, the cultivated valley floor, with cereals such as barley and wheat, temporary and permanent meadows, and aromatic and medicinal plant crops (lavender and sage)

Fig. 1 Typical landscape of the Vallée des Duyes in the South of France. One can distinguish the four main landscape characteristics of this area: large cultivated plateaus, grasslands, rangelands, and forest

- In the west of the middle valley, the cultivated plateau and two dense and continuous cultivated areas on the slopes
- In the east and in the north of the valley, moorland areas grazed by ovine herds

We characterize four types of farming systems, spread differently between each area of the territory (Fig. 2): specialized crop, specialized livestock, and two mixed crop-livestock farms (differing by livestock size and farm areas):

- Specialized crop farms in plateaus: farms specializing in field crops, cereals, and aromatic plants (lavandin)
- Specialized livestock farms on moorlands: farms specializing in livestock farming without field crops but with temporary meadows
- Mixed farms on both crop, and permanent and temporary meadows:

– A small mixed farm with livestock and a cash crop (wheat). The livestock mainly grazes local meadows.
– A large mixed farm with livestock, a cash crop (wheat), and an aromatic plant (lavandin). The livestock grazes both meadows and rangelands but also uses summer pastures.

2.2 Simulation model

The description of the model follows the overview, design concepts, and details (ODD) protocol originally used for describing individual and agent-based models (Grimm et al. 2010) but adapted here for a simulation model based on interactions between a diversity of farms. The ODD protocol consists of seven elements. The first three elements provide an overview, the fourth element explains general concepts underlying the model's design, and the remaining three elements provide further details.
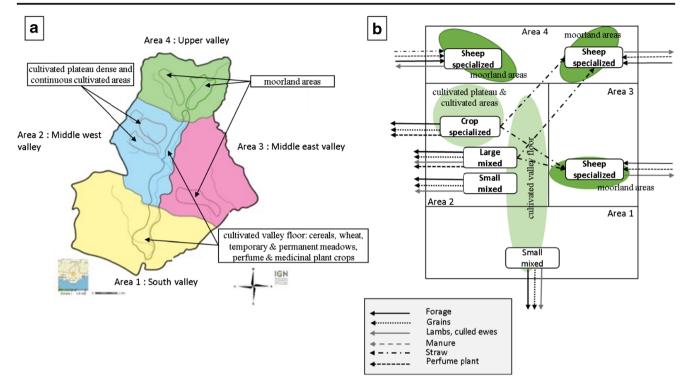
2.2.1 Purposes

The model developed here represents the diversity in the organization of several farms that compose a territory. It assesses the impact of this diversity on the sustainability of agricultural activities by simulating the interactions between crop and livestock activities within and between farms. In particular, it aims at comparing various territory configurations. Each configuration corresponds to a specific distribution of several types of farms within the territory.

2.2.2 Entities, states, and scales

We model the agricultural activities within the Vallée des Duyes. From a landscape analysis, coupled with the French national databases (French geographic census of agriculture) and the database of the Inosys network (Bataille 2016), the several types of the farm situated on the geographic area studied are listed. A scheme of their distribution is defined.

We therefore model four types of farms representative of these agricultural activities. The farm submodels operate as an average year. The territory configuration model runs for 1 year.

Fig. 2 Overall graphical representation of the territory configuration model building. **a** A schematic illustration of the four areas cutting into the Vallée des Duyes territory and their land use. **b** The configuration of several types of farm distribution for the current situation in the four land use areas described in **a**

At the farm and territory configuration scales, a large panel of static variables are used to describe both the functioning of the crop and livestock activities and their annual output indicators distributed within four dimensions (production, environmental, economic, and social) (see these dimensions in Tables 1 and 2). These indicators correspond to the sustainable properties of farms and territory. The effect of diversity is therefore measured on these indicators.

2.2.3 Process overview and scheduling

Five main processes are modeled within several time scales. The different processes related to the farm submodels and the territory configuration models are listed here.

For each farm submodel, modeled processes are as follows:

- Areas and calculations of mowing yield and standing grass production (available on pasture)
- Herd size by time of year with periods divided into feeding periods and animal physiological stages (e.g., batch of pregnant females during spring)
- Herd feed, including type of feed (concentrates, forage, standing grass on pasture or rangeland) by time of year and corresponding herd size
- Economic balance sheet calculated on the basis of gross income, subsidies, and farm loads

The herd demography or the daily/seasonal growth of biomass on pastures is not modeled because we only needed to obtain the yearly result.

For each territory configuration model, the aggregation of individual farm submodels is represented.

An overall graphical representation of the implemented model appears in Fig. 2.

2.2.4 Design concepts

Basic principles A consensus around the interest of increasing diversity to obtain more sustainable systems is highlighted in literature. To explore this relationship, we chose to compare sustainability of various territorial configurations according to how the diversity is built within and between farms. Starting from an initial configuration based on specialized and diversified farm types (Ref-config), we simulate two territory configurations based on the diversity of specialized farm types (MultiSpec-config) and a territory based on diversified farm types (Mix-config) (Fig. 3).

Emergence The indicator of diversity emerges from the land use distribution within farm-land area and within the territory land use (according to farms that compose the territory configuration). Obviously, all output indicators at the farm scale emerge from their own intrinsic

Table 1 Characteristics of the four farms modeled: structure, land use, livestock and crop management, economic performances, sensitivity, and diversity indicators. Figures in italic characters correspond to the indicators selected for assessing the farm sustainable properties. Sources: Idele (1999) and Bataille (2014)

Farms Structure: general description of the farming system	Sheep specialized farm Transhumant herd, local meadows, and rangelands	Small mixed farm Sedentary herd	Large mixed farm Transhumant herd, rangelands close to farm, grassland in summer pasture	Crop specialized farm Production of crops, cereals, and perfume plants (lavandin)
Worker (nb.)	1	1	1.5	1
Total arable lands (ha)	43	62	111	105
Proportion of grazed lands (ha)	31	53	101	105
Flock size (nb.)	354	320	500	0
Stocking rate (ewes per ha)	11.4	6	5	n.a.
Land use				
Crop lands (ha)	0	42	86	105
Part for livestock feed (ha)		11	11	
Forage lands (ha)	32	20	25	0
Rangelands valued (ha) (except summer pasture)	389	178	522	0
Livestock management				
Forage need for the flock (TDM/year)	92	70.7	85	n.a.
Proportion of grazing in feed in tons of dry matter (TDM) (proportion of rangelands)	153 (110)	135 (52)	278 (218)	n.a.
Proportion of rangelands in feed	0.13	0.1	0.17	n.a.
Concentrates per ewe (kg per ewe)	0.65	0.85	0.74	n.a.
Forage autonomy	1.04	1.07	1.19	n.a.
Animal feeding costs per ewe (in euros per ewe)	20.4	28.2	30.6	n.a.
Crop management				
Organic fertilization (tons of manure/ha of arable lands)	0	15	24	0
Mineral fertilization (unit of N/ha of arable lands)	17	61	63	84
Economic performance				
Total income (in euros)	20,822	36,293	62,355	56,056
Income per ha of arable lands (in euros per ha)	484	585	561	533
% of income from animal production (% of total income)	30.1%	41.6	68.9%	n.a.
Economic production efficiency	71.0%	68.9%	67.5%	71.3%
Of crops (economic production efficiency)	n.a.	68.6%	71.9%	71.3%
Of livestock (economic production efficiency)	71.0%	69.1%	62.1%	n.a.
Proportion of subsidies in the income/dependence to subsidies (%)	239%	121%	83%	43%
External input dependencies (in euros per 100 euros of products)	6.85	7.64	29.11	35.5
Resilience indicator				
Resistance to economic shock	0.802	0.872	0.78	0.765
Variation coefficient of income faced with an economic shock	21.9	10.9	16.0	21.8
Diversity indexes				
Shannon diversity index for land use	0.876	1.154	1.178	0.314
Shannon diversity index for products	0.438	1.075	1.279	0.646

na. not applicable

nb. number

characteristics. At the territory configuration level, the output indicator values result from both the individual farm characteristics and from the interactions between them.

Interactions Interactions between crop and livestock occur both between and within farms. Within farms, the interactions involve the animal feed by production forage or cereal in arable lands. Between farms, the

Table 2   Characteristics of the three territory configurations modeled: structure, land use, livestock and crop management, economic performances, sensitivity, and diversity indicators. Figures in italic characters correspond to the indicators selected for assessing the sustainable farm properties

Territory configurations	Ref-config	MultiSpec-config	Mix-config
Configuration			
Sheep specialized farms	0	17	0
Small mixed farms	6	0	25
Large mixed farms	8	0	7
Crop specialized farms	14	19	0
Structure			
Worker (nb.)	32	36	35.5
Flock size (nb.)	5918	6018	11,498
Total arable lands (ha)	2730	2726	2328
Proportion of grazed lands (ha)	1212	527	2060
Stocking rate (ewes per ha)	4.9	11.4	5.6
Straw sold within the territory (TDM)	6	0	7
Land use			
Forage lands (ha)	320	544	675
Crop lands (ha)	2190	1900	1582
Rangelands valued (ha) (except summer pastures)	5270	4004	8105
Livestock management			
Forage need for the flock (TDM/year)	1046	1462	2127
Concentrates per ewe	0.84	0.66	0.77
Forage autonomy (%)	116%	105%	110%
Crop management			
Organic fertilization (tons of manure/ha of arable lands)	10.2	0	18.3
Mineral fertilization (unit of n/ha of arable lands)	84.2	72.8	79.5
Economic/technical performance			
Total income (M€)	1.489	1.419	1.291
Income per ha (€/ha)	545	563	554
% of income from animal production (% of total income)	30.1%	41.6%	38.9%
Economic production efficiency	70.0%	71.2%	68.8%
Of crops (economic production efficiency)	71.2%	71.3%	69.7%
Of livestock (economic production efficiency)	64.7%	71.0%	67.7%
Proportion of subsidies in the income/dependence to subsidies (%)	73%	65%	113%
External inputs dependencies (in euros per 100 euros of products)	29.3	17.8	14.9
Animal feeding costs per ewe (in euros per ewe)	26.1	40.3	23.7
Resilience indicators			
Resistance to economic shock	77.9	76.3	84.8
Variation coefficient of net income faced with an economic shock	17.3%	16.8%	12.3%
Diversity indexes			
Shannon diversity index for land uses	0.741	0.579	1.158
Shannon diversity index for products	1.626	1.156	1.110

nb. number

interactions occur only for the sale of straw from specialized crop farms or large mixed farms to small mixed farms. Currently, the cereals bought to feed herds do not originate from neighboring crop farms but come from national or regional industrial firms.

Stochasticity In this model, we model only mechanistic processes with deterministic parameter values. We therefore do not use stochasticity.

Collective The collective scale of our model corresponds to the territory configurations. These configurations are represented by different distributions to several types of farms within the territory. The territory configurations are therefore the aggregation of the results obtained at farm scale and the interactions between farms. Thanks to the different territory

configurations, the model provides insights into the impact of the diversity of farm compositions as well as that in the organization of the crop and livestock activities at both the farm and territory scales.

Submodel and observations: indicators for comparison All information on parameters and variables involved in the farm submodels appears together in Table 1. Information on territory configurations appear in Table 2.

Here, we detail the indicators of diversity and performances at both farm and territory scales. To model several sustainability indicators (economic, technical, management, environmental, and social dimensions), we used the variables in the model (corresponding to the input data that describe the intrinsic characteristics of the farm and that appear in Table 1). The indicators are grouped into seven sections: structure, land
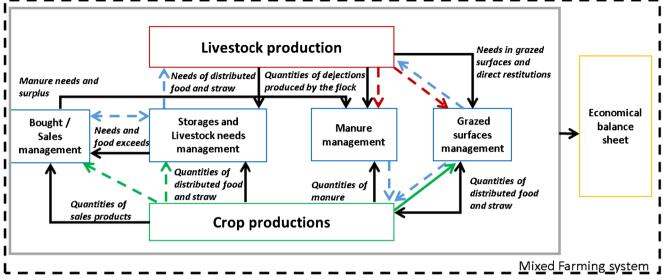
Fig. 3 Conceptual framework of the mixed farms: The same framework is used for the large and small mixed farms with a representation of the livestock, crop, and economic components. The specialized crop farm does not present the livestock component, and the specialized livestock farm does not present the crop component

use, crop management, livestock management, economic performances, resilience indicators, and diversity indicators. Among these indicators, some needed intermediate calculations which are described below:

- Economic production efficiency: $Eff_{ProdEco} = \frac{GP - OpeL}{GP}$, with GP, the gross product, and $OpeL$, the operational load.
- Dependence to subsidies is the ratio of the subsidies to the net income of farm.
- Forage autonomy is the ratio of the forage produced to the forage distributed.
- External input dependencies (in euros per 100 euros of products): $Dep_{input} = \frac{cost\{fertizer, concentrates\}}{GP - Subsidies} \times 100$, with cost{fertizer, concentrates}, the cost of the fertilizer and the concentrates bought.

Among the frameworks which relate resilience and sustainability concept described by Marchese et al. (2018), we place ourselves here in the sense that resilience is a component of sustainability. The resistance to shock reflects the ability of the agricultural systems to absorb the shock and then to be more resilient. As a resilience indicator, we therefore model the impact of an economic shock, measured at both farm and territory configuration levels. An increase of 20% in the price of inputs (fertilizer and concentrates) and/or a 20% decrease in product prices (lamb, grain, and lavender) is applied. Simulation experiments comprise combinations of variations for the five parameters (input and output prices) and results in 32 experiments. Two indicators are calculated: a score of resistance to shock R is calculated with $R = 1 - (I_{max} - \frac{I_m}{I_{max}})$; I_{max} is the highest value of income obtained for the 32 simulations, and I_m is the mean income, with a coefficient of variation of income, $CV = \frac{\sigma}{\mu}$ (expressed in %).

For the farm submodels, two diversity scores are calculated to assess the diversity (i) in the land use and (ii) in the products provided (Funes-Monzote et al. 2009). The Shannon index (I_Prod) of product diversity equals: $I\_Prod_X = -\sum_{k=1}^{S} p_k \ln p_k$, where S is the number of products and p is the proportion of the products within the total landscape production (in euros). For example, for the diversity of production, the Shannon index combines either the number of products (richness S) with the yield per product (abundance). The same equation is used for the Shannon index of land use diversity but involves the surface of each type of land use (crop, forage, grazing, rangelands).

The indicators of performances at the territorial scale are the same as those at the farm scale. They correspond to the sum of the individual results of the farms composing the configuration, taking into account the interactions between them.

The final discussion on the impact of diversity on the sustainability of agricultural systems is based on a selection of the most suitable performance indicators (in italics in Tables 1 and 2).

Initialization The initial values of the variables used in the farm submodels are presented in Table 1, and those used in the territory configuration model are presented in Table 2. They correspond to the values of the modeled reference territory.

Input data The model is built on the farm's database, provided by the Inosys network (Bataille 2016), which models typical

cases of livestock systems that correspond to systems encountered in our study territory.

2.3 Simulation experiment

To explore the impact of the diversity on the sustainability of agricultural activities at higher level than farm, we model three territory configurations. As explained in the following sections, a configuration is a specific distribution of several types of farms within the territory.

2.3.1 Baseline scenario

The first configuration modeled is the reference one (called Ref-config), which is based on the landscape analysis and the database for the Inosys network (Bataille 2016). The Ref-config is composed of 14 specialized crop farms, 6 small mixed farms, and 8 large mixed farms.

2.3.2 Simulation principles and constraints

Based on the reference territory configuration, we simulate different configurations to test our hypothesis of the impact of diversity on sustainability.

To be realistic with territorial characteristics and agricultural orientations, we take into account some constraints to simulate alternative configurations:

– Allocation of areas: Pasture land and arable land are not commutable according to their agronomic potential and constraints (mechanization).
– Farm types in areas 3 and 4 of the territory are not modified because lands can only be valued by specialized livestock farms (mainly rangelands).
– To be consistent with actual livestock production level, alternative configurations have to come closer to 5900 ewes (when it is possible).
– We make the assumption that the new territory configurations modeled have to keep the same amount of cultivated land. The reference configuration corresponds to 2500 ha of arable land.
– However, the size of exploited rangelands is 7000 ha, and we assume that the rangeland surfaces valued can be increased up to 30%, according to territorial characteristics.

2.3.3 Alternative configurations

To test our hypothesis, we model two contrasted alternative configurations of the reference territory. Since the reference territory configuration corresponded to both specialized and mixed farming systems, we propose to simulate a multi-specialized one (MultiSpec-config) based on specialized crop and livestock farm types and a mixed one (Mix-config) based on mixed farms only (small and large). Consequently, we adapt the distribution of farm types in the territory to provide new territory configurations (Table 2).

The MultiSpec-config provides insight on the impact of the diversity and the possible complementarity between specialized farms at territorial scale. Taking into account the land use and the total livestock size constraints, 19 specialized crop farms and 17 specialized livestock farms compose the MultiSpec-config. This includes 2518 ha of arable lands, 5835 ha of rangelands, and 6018 ewes.

The Mix-config provides insight into the impact of the diversity and the possible complementarity within diversified mixed farms at territorial scale. To model this configuration, we have to maintain only the small and large mixed farming system types in the territory configuration. However, their characteristics do not permit maintenance at the same level as land use and livestock size constraints. Therefore, we implement a configuration that minimizes the livestock size while maintaining the land use constraints, with mixed farming types having a higher number of ewes per hectare of arable land. The Mix-config is therefore composed of 25 small mixed farms and seven large mixed farms. It includes 2850 ha of arable lands, 8105 ha of rangelands, and 11,500 ewes.

3 Results and discussion

3.1 Individual farm structure diversity and performance

Specialized livestock farms The specialized livestock farms have little land compared to the others (Table 1) and correspond to less than 50% of specialized crop farm areas, for instance. The ewe load is high on grassland (grouping lands of farms that are grazed), but this type of farm compensates for the large use of rangelands in the animal diet. The specialized livestock farms, as well as the large mixed farms, use a little more than 1 ha of rangelands per ewe, which is twice the size of the small mixed farms. This does not allow them to restrict their feed cost per animal, which exhibits the highest value (ranging between 24 and 18% more). These farms show the lowest income among the modeled farms. However, the specialized livestock farms exhibit a high resistance when undergoing economic shocks. This resistance is accompanied by both (i) a low dependence on external inputs, resulting from little use of mineral fertilizer, and (ii) a high proportion of subsidies in the income, whose value does not vary during economic uncertainty. Among the 32 experiments of the economic shocks modeled, this farm type is the only one that is not affected by the shocks applied on the fertilizer price. It results in a low exposure to shock and consequently to a high

resistance indicator. When this system is exposed to the shocks, the farm is very vulnerable because a high dependence to the concentrates was bought (three times higher than the other farms with animals).

Small mixed farms With a flock size close to 350 ewes, the small mixed farm size corresponds to half the size of the other two farms with livestock (Table 1). It appears as a more intensive system, with more concentrates distributed per ewe, a lower use of rangelands (the rangeland feed intake is half that of other farms), and a higher use of grasslands for livestock grazing. The animal diet is equally distributed between forage distribution, grassland grazing, and rangeland grazing. The amount of concentrates per ewe is 24% higher than that of specialized livestock farms and 13% higher than that of large mixed farms. The small mixed farms have a lower economic efficiency of production than specialized farms but a higher value than large mixed farms. However, the small mixed farms show the highest resistance indicator and the lowest variation of input price fluctuations thanks to a low dependence on inputs coupled with a low dependence on subsidies. A low dependence on inputs is related to low exposure of their price variation. A low variation is due to a combination of low exposure to shock and income mainly built on subsidies, which are a kind of compensating buffer. It therefore results in the high resistance indicator.

Large mixed farms The large mixed farms show a more pastoral profile compared to the small mixed farms. They use large rangeland areas, complete with summer pastures. Only large mixed farms, which associate larger area and flock, are accompanied with more workers. This fact is accompanied by the larger area of arable land associated with a flock size 1.5 times higher than other farms that own livestock (Table 1). However, it also exhibits a very high use of mineral fertilization, which makes it highly dependent on inputs. This high dependence leads to a low resistance to economic shocks. The large mixed farms also have the highest feed cost compared to other mixed farms. It is due to summer pastures, which are expensive compared to the use of local meadows, and leads to a decrease in economic production efficiency (especially the livestock economic production efficiency). Despite these aspects, this type of farm has the highest income per worker than other farms that own livestock.

Specialized crop farms The specialized crop farms earn the highest income per worker (Table 1), whereas the highest income for small mixed farms is earned per hectare. The high use of mineral fertilizer on crop lands for specialized crop farms results in a strong dependence on inputs. Consequently, this type of farm undergoes a strong impact of price fluctuations on income, reinforced by its low

dependency on subsidies compared to other farm types (for instance, twice as low as large mixed farms).

Individual diversity indicators The diversity in land use in the specialized crop farm is lower than that in the other farms (Table 1). The three farms that own livestock differ in their surface area allocation. The value of their Shannon index reveals this difference, accounting for the size of these surfaces and their proportion used for animal feeding or cash crops. For example, the specialized livestock farm has a lower index than the other two farms, because of the absence of cash crops. For this diversity indicator, the two mixed farms have similar values and are quite different from specialized farms. The same can be observed for the diversity of products, which logically earns the highest values for mixed farms, which provide a wider range of products than specialized farms. The large mixed farms reach the highest value for the two indicators of diversity. In contrast, the specialized livestock farms have the lowest product diversity index, lower than the specialized crop farms.

3.2 Diversity in territory configurations and associated performances

Comparisons of territory configurations led to the conclusion that the trade-offs between performances (technical, economic, environmental, diversity, and sensitivity) occur according to the proportion of farms within the territory (Table 2).

The reference configuration Compared with the other territory configurations, Ref-config exhibits the highest total income, and therefore the highest income per worker, given that the number of workers exhibits its lowest value (four less than MultiSpec-config and 3.5 less than Mix-config). Ref-config diversity indicators show that this configuration makes it possible to combine a high product diversity with a relatively diversified use of land, divided between crop and animal use. The diversity of the types of farms that compose this configuration present both extensive profiles (for large mixed farms that value much rangeland) and intensive profiles in the use of grassland and cultivated areas (for small mixed farms and specialized crop farms). Ref-config provides a good balance of economic, environmental, and production indicators. Thus, Ref-config also presents an intermediate sensitivity to economic shocks. Actually, it associates farms with the opposite results for this indicator, which leads to a rather good indicator value at the territory scale. In contrast, by associating the two types of farms that use the highest mineral fertilizer amounts, the value of the indicators of the dependence on external inputs presents the worst results compared to the other configurations.

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The multi-specialized configuration MultiSpec-config accounts for the largest number of workers in the territory but with an income per worker lower than Ref-config. However, the income per hectare is slightly higher than other territory configurations (20 euros more than Ref-config and 10 euros more than Mix-config). It presents the lowest use of rangelands up to twice as low as Mix-config. This decrease is due to the livestock size in this configuration rather than the rangeland use per animal, which remains equal to Mix-config. The use of mineral fertilizer corresponds to 7 and 12 units of N per hectare less than Mix-config and Ref-config respectively. For this configuration, the lowest dependency to subsidies and the highest dependency to external inputs result in a resistance to economic shock approximately 7 points lower than that for the two other configurations. In contrast, MultiSpec-config shows the best economic production efficiency compared with crop or livestock specialized farms. This can be explained by the fact that this configuration regroups the two types of farms that exhibit the highest values for this indicator. The high feeding cost per ewe provided by the specialized livestock farm, which is approximately 20 euros per ewe higher than the other configurations, seems to have no effect on the good economic efficiency of MultiSpec-config. Even if this configuration is only composed of specialized farms, the product diversity score is higher than that of Mix-config. It is indeed the combination of the two types of farms that makes it possible to obtain this indicator value at a collective scale.

The diversified configuration Mix-config achieves the highest diversity score in area use, with an area equally distributed between cash crop production, animal feeding, and pasture and rangeland grazing. The rangelands are more valued than in other configurations, approximately twice as high as MultiSpec-config and 1.5 times as high as Ref-config. In this configuration, the use of organic fertilization involved in mixed farms places value on within-farm interactions between crops and livestock. These interactions are almost twice as high in Mix-config than in Ref-Config and do not exist in MultiSpec-config. The same result is observed for farm interactions represented by straw sales. Despite the use of organic fertilization, these interactions present a high amount of mineral fertilizer use (close to the value obtained by the reference territory). The income exhibits its lowest value, although the income per hectare is higher than that in MultiSpec-config. Mainly composed of small mixed farms, this territory configuration results in a lower dependence on inputs. Added to a high dependence on income from subsidies, it induces a low sensitivity to economic shock reflected by the highest resistance to variation in input prices (and also the lowest variation coefficient). Even if Mix-config allows provisioning for a wider range of products equal to MultiSpec-config, it shows the lowest value for the diversity indicator, which reflects an unbalanced distribution of the products.

3.3 Diversity and sustainability in agricultural systems

3.3.1 How diversity is measured alters its impact on the sustainability of agricultural systems

At the farm level, the functioning of livestock and crop activities is intrinsically linked to the way in which land is used. This diversity thus illustrates the separation of areas for the use of land for livestock (forage or cereal production and grazing) or for cash crops. The management of feed systems and crop lands leads to a dependence on inputs and subsidies that affect the ability of farms to withstand economic shocks (here, this means variation in the price of inputs). We note all the same that, depending on the diversity measured (that of products or that of land use), the conclusion regarding the relationship between this diversity and the properties of the sustainability of the systems does not always point in the same direction.

Some authors show that diversity in farming activities may increase income stability and reduce the income risks of resource-poor households (Farinelli et al. 2018; Niehof 2004; Pacin and Oesterheld 2014). However, beyond comparing mixed and specialized systems, some authors have shown that, as in the present study, the organization of activities provided by farm practices can lead to an impact on farm sustainability performances, such as vulnerability, within-farm interactions, and self-sufficiency (Lin 2011; Martin and Magne 2015; Sneessens et al. 2016; Stark et al. 2016).

However, the definition of diversity and its calculation differs among studies, and conclusions about the impact of agricultural activities within and between farms on farms' sensitivity to hazards can vary tremendously. Thus, to assess the impact of the diversity of agricultural systems, some authors test the impact of variety changes on crop surfaces, while others investigate the impact of grazing or mowing practices or the changes in animal management that modify the need for cut or standing fodder (Martin and Magne 2015; Sanderson et al. 2013). Some authors also test different forms of organization of crop and livestock activities on a farm (Sneesens et al. 2016). However, few authors use a quantified measure of this diversity. Some use the Shannon index (combining index of richness and frequency: Bernues et al. 2011; Pacin and Oesterheld 2014), while others calculate the diversification of production (Ripoll-Bosch et al. 2014). Few studies attempt to translate the impact of changing practices into diversity scores to compare different systems and their ability to withstand hazards (Pacin and Oesterheld 2014) or their ability to provide services. Here, we used two measures of Shannon diversity indicators to translate both crop and

livestock management and the more-or-less diversified composition of territory. These indicators help to better understand how these diversity levels built at several scales impact the sustainability of agricultural systems.

3.3.2 Importance of considering a set of performances to assess the impact of diversity

The impact of various diversity measures is assessed on a large panel of economic, production, and environmental performances but rarely in the same study. For instance, the impact of farm diversity is assessed on the ability of systems to maintain food autonomy (Martin and Magne 2015), to maintain a level of ecosystem service delivery (Sanderson et al. 2013), to allow flexibility (Rippol-Bosch et al. 2017), or to withstand weather or economic hazards (reflected in biomass growth variability (Martin and Magne 2015) or on business indicators (Farinelli et al. 2018)). In this study, we chose to work on a set of performances at both the farm and territory scales. The study highlights that a critical challenge is to identify and accurately assess trade-offs among desired performances for maintenance or improvement. For example, maintaining acceptable income per worker on a territory may compromise the surface of rangelands valued. Here, we note that an increase in the number of workers at territory scale can be reached, but it is coupled with a decrease in the income per worker. This individual result for farmers appears therefore less interesting than the collective result and reveals a trade-off between the two scales. When combining several types of farms at the territory level, the diversity score appears to be rebalanced. For instance, in MultiSpec-config, the product diversity reaches the highest value associating the two types of farms, which exhibit the lowest individual score. However, it is the opposite for the land use diversity indicator, which remains the lowest compared to the two other territory configurations. For the diversity indicator, all performances assessed in each territory configuration are also impacted by the type and distribution of farms.

However, in our study, the results obtained are mainly obvious because we have introduced few interactions between the different farms. Actually, only current practices in the Vallée des Duyes are simulated, and interactions between farms are not strong. One strategy could be to test the impact of practices that promote linkages between farms, such as the introduction of legume plants in crop rotations, a larger use of organic fertilization, or local sales of forage. Such practices would modify the impact of integration within and between farms and would affect the sustainable properties to the agricultural systems. On the other hand, a measure of the interaction within and between farms, such as the ecological network analysis (Stark et al. 2018), should be relevant to assess the stability of the farming systems. In this case, the interactions within a farm are represented as a network of nutrient flows. The authors concluded that the most diversified and complex flow networks of nutrients contribute to the agroecological performance of mixed crop livestock farms, enhancing productivity, efficiency, self-sufficiency, and resilience.

3.3.3 Trade-offs between performance levels as a consequence of direct and indirect effects of crop and livestock organization at farm and territorial scales

At the farm level, our results show that the diversity indicators cannot directly explain a farm's sensitivity to price variation. Farm characteristics, such as the proportion of rangeland in livestock diet and the dependence on external inputs and/or subsidies, have to be considered as potential factors in leveraging sensitivity and economic shock. The specialized ovine farms do not use mineral fertilizer but rather concentrates for animal feeding. Our simulation of variation in fertilizer price does not directly affect the farm; however, in contrast, this is the only farm that is affected by an increase in the concentrate price (and the impact is strong when it occurs). The exposure of farms to shock varies according to their own characteristics. This result can explain why the income variation of this farm is similar to that of the specialized crop farm but higher than that of the mixed farms. Among mixed farms, fertilization practices induce slight differences in terms of dependence on external inputs between small and large mixed farms. Actually, the use of manure to fertilize crop lands within mixed farming systems could lead to less dependency and fluctuation in mineral fertilizer prices. Whereas this is true for the small mixed farms, the large ones use both organic fertilization and a high amount of mineral fertilizer.

Bernues et al. (2011) concluded that pasture-based livestock farms are less vulnerable to market changes than other systems. In contrast, our results show that the highest resistance to economic shock is provided by the small mixed farm that uses less than half the feed intake in pastures than other livestock farms. The proportion of pasture intake and rangeland intake is also a component to take into account when assessing the vulnerability of farms. On the other hand, in terms of drought effects, Lawes and Kindwell (2012) show that farms that allocate more than 50% of their area to crops are more resilient. In a study analyzing the impact of diversification on the economic stability of farms in Argentina, Pacin and Oesterheld (2014) show that a greater diversification of activities was associated with an increase in stability (associated with a lower coefficient of variation in the return on capital). This is not the case for the mixed farm we modeled. The large mixed farms exhibit a higher diversity indicator value than the small mixed farms but with a lower resistance to economic shock. Unlike us, in literature, the specialization of farm to livestock activities seems to

highlight higher income than diversified farms. Actually, Pacin and Oesterheld (2014) shows that specialized livestock farms and mixed farms with an activity of more than 33% associated with livestock have a higher income than other farm types. For our study, the calculation of the Shannon index is based on the distribution of activities on the farm's areas. Moreover, we conclude with the calculation index according to the division of the gross products from the various productions of the farm.

As demonstrated in our study, other authors have shown that in addition to diversity criteria, dependence on external inputs (linked to feed self-sufficiency) or on subsidies is often highlighted to impact the sensitivity of farming systems to hazards (price fluctuations or droughts). Ripoll-Bosch et al. (2014) draws three conclusions: low off-farm input dependence and enhanced feed self-sufficiency is crucial to labor profitability, animal productivity is important for economic autonomy (reducing subsidy dependence), and the diversity of the production mix enhances farm flexibility. We have the same observations. Actually, at the farm level, farms that are less dependent on external inputs appear to be more resistant to economic shock. Being less dependent to inputs, they are less exposed to their price variation. In socio-ecological systems such as agricultural systems, the low exposure to shocks refers to their vulnerability (Adger 2006). Their ability to absorb the shock when they are exposed therefore refers to their resilience (Walker et al. 2004). Likewise, for Toro-Mujica García et al. (2012), Spanish farming systems try to integrate agricultural and livestock activities to reduce dependence on external inputs and achieve greater income stability. In the mixed farm we model here, this stability depends strongly on fertilization implementation methods in both cash crops and forage lands. However, the high resistance to shock is also due to high access to subsidies. It can be assumed that the subsidies received are stable each year when the farms are in average operation (no changes in area and herd size in progress). The higher the subsidies, the more it helps to mitigate the impact of a change in input prices.

Just as we have tested the impact of a variation of input prices on income, we could have tested the impact of climatic hazards on fodder autonomy. Actually, the response of other indicators to a change in the market or environmental components should provide insights to help us understand trade-offs at the individual and collective scales (such as indicators from lifecycle assessment; O'Brien et al. 2016.

In addition, future studies should address both the impact of climatic hazards and price variation on territory sensitivity simultaneously. Indeed, Mediterranean agroecosystems are strongly constrained by these perturbations (Aguilera et al. 2020). One can manage several indicators at the field, farm, and territory scales to explore all dimensions of sustainability and to encourage agroecological regional development. These studies would then be complementary to those already published, particularly in rural geography, to quantify the diversity in the spatial organization of the agricultural activities.

4 Conclusion

The intrinsic diversity of individual farms allows us to partly understand how these diversities impact the sustainability of agricultural systems on the farm and territory level. A farm's structure and function are drivers of land use division between crop and livestock activities. At the farm scale, mixed farms exhibit high values of diversity indicators and present high values for the majority of sustainable properties. In spite of good results at the farm scale, the mixed configuration at territorial scale is not as markedly different from other configurations. This configuration shows the highest resistance to economic shock, but economic performances are lower than the reference and the specialized configurations. Trade-offs among performances occur at both the farm and territorial scales, leading to pairing the diversity of territory composition with the diversity within farms to understand how to design sustainable agricultural systems at various scales.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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