MIXED
EFFICIENT AND RESILIENT
MIXED FARMING & AGROFORESTRY

MIXED

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Summary

This deliverable explores the role of interactions among farmers as a foundational element for building mixed and resilient landscapes. We define farmer interactions as coordinated, direct or indirect actions between two or more actors (with at least one being a farmer) that lead to exchanges of goods, animals, or services, contributing to nutrient recycling and landscape services provision. These interactions are particularly important when they occur between specialized but complementary farms (farms might not be mixed, but "mixedness" emerges at the level of landscape). To investigate their significance, we developed a conceptual framework and conducted three analyses (two are semi-qualitative and one is based on agent-based modelling) to assess their impact on mixed landscapes. 1) The first analysis explores interactions across 6 case studies, identifying key factors, barriers, and levers that influence these exchanges. 2) The second analysis explores farmers' motivations for engaging in interactions, focusing on the French case study (Ariège), where more detailed interviews with a network of farmers were conducted. 3) The third analysis simulates farmer interactions, exploring potential future scenarios (observable at the level of whole landscape) by adjusting factors such as connectivity and trust. These simulations made it possible to assess the impact of farmer interactions on landscape resilience and mixedness. Our findings emphasize the critical role of interactions in fostering mixedness at the landscape scale. However, not all interactions contribute equally to mixedness (some might be oriented purely at economic development or food production), and careful attention is needed to ensure that they lead to nutrient recycling (also passing through quantification of the exchanged involved). The semi-qualitative analyses showed that logistics, proximity among farmers, and social networks also play key roles in the success of farmer interactions, while barriers such as climate change and bureaucratic constraints must be taken into account for policymaking. Interactions are often based on informal contracts, so the importance of balancing formal and informal contracts is discussed, with policy recommendations focusing on building trust, promoting flexible contracts, and supporting long-term partnerships for agroecological transitions. Simulations with agent-based modelling emphasized the importance of balancing collective and individual resilience and benefits, making sure that landscape resilience is built on benefits equally distributed among all the farmers.

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Abbrevations

Abbreviation	Definition
ABM	agent-based model
FM	fresh matter
DM	dry matter
dml	dimensionless
LU	livestock unit (Eurostat, 2020)
MiFAS	mixed farming and agroforestry systems (here particularly at landscape level)
NUTS	Nomenclature of Territorial Units of Statistics
ODD	Overview / Design concepts / Details (Grimm et al., 2020)
UML	Unified Modeling Language
WP3	Work package n°3 of the MIXED project

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1 Introduction

In previous deliverables, D6.1 (Accatino, 2021) and D3.2 (Grillot and Accatino, 2022), we clarified the meaning of mixed farming and agroforestry system (MIFAS), using also the concept of "mixedness", which refers to the integration among components (e.g., trees, grass, livestock). We highlighted that the achievement of mixedness comes with two elements: diversity of elements and interaction among them. The basic hypothesis of the MIXED project is that mixedness increases resilience and efficiency. We highlighted that the concept of mixedness has different nuances according to the level considered. At the farm level, the focus is on the integration of individual practices. However, at the landscape level, specialized farms can contribute to nutrient recycling and integration if they interact in some way with other specialized – complementary – farms (Martin et al., 2016). For instance, the exchange of manure between livestock farmers and feed between crop farmers exemplifies how interactions can promote nutrient recycling and integration among landscape components. This deliverable addresses the interactions among farms.

In Chapter 2 we aimed at providing the general framework upon which the concept of interactions for mixed landscape is built. After this we developed our analysis of interactions along three steps. In the first step (Chapter 3) we performed a transversal analysis of all the types of interactions involved in the WP3 case studies. This first analysis served for characterizing the interactions, getting a first overview of the main factors (lever and barriers) affecting interactions, making some considerations about those interactions leading to increased nutrient circularity and mixedness, and finally having some considerations about interactions among farmers in the case studies explored and some insights for policy making. In the second step (Chapter 4) we aimed at diving more in detail into the reasons encouraging farmers to interact. This second analysis was done specifically in the French case study (Ariège), where more in-depth interviews were possible with a network of farmers. In the third step (Chapter 5) we aimed at analysing the behaviour emerging from farmer interactions at the level of farmers. In this third step we ran scenarios changing parameters typical of relationship among farmers, such as connectivity or trust among farmers. The modelling simulations allowed to explore possible future with configurations which are not currently existing and therefore to test hypotheses. The model is applied starting from the information coming from the French case study (Ariège). The overall analysis of interactions allowed getting some new knowledge about the role of interactions in mixed systems.

Papers submitted, accepted and in preparation for international peer-reviewed communications are listed in Appendix A. Chapters 1, 2, and 6 were developed by the task leaders (INRAE) whereas specific author contribution statements are provided at the beginning of the other chapters.

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2 Overview of the concepts and methods involved

This section introduces the framework used for the definition of interactions for MIFAS and discusses the contribution of the different methods used in this deliverable for the analysis of interactions.

2.1 Conceptual framework

As a first step, it is important to define an interaction in the context of this analysis. We define an interaction as a *coordinated direct or indirect (e.g., via intermediaries) action between two or more actors (they are generally two farms but it can also be one farmer and another type of actor) that leads to a permanent or temporary exchange of goods or animals providing some services (e.g., improved soil condition, animal welfare, increased nutrient recycling).* Money can be involved in the exchange, however, in order to be considered an interaction a landscape service should also occur as a consequence of the transaction.

A framework (Figure 1) puts this definition in a bigger context, conceptualising the structure of a landscape. We consider a landscape as an entity composed by a farmland ecological system (biophysical component) as well as farmers and any other relevant actors, as for example advisors, biogas plants, or processors (socio-economic component).

The interaction consists of an exchange of elements (e.g., biomass, livestock) between two farmers or between one farmer and another actor (e.g., a farmer sends manure to a biogas plant and receives digestate) which generates a positive impact on the biophysical component in at least one of the two farms or in the landscape (the landscape in general or a part of the landscape outside the farms involved). The elements of this framework will be important in order to understand the differences between the methods and to describe the interactions in the qualitative analysis.

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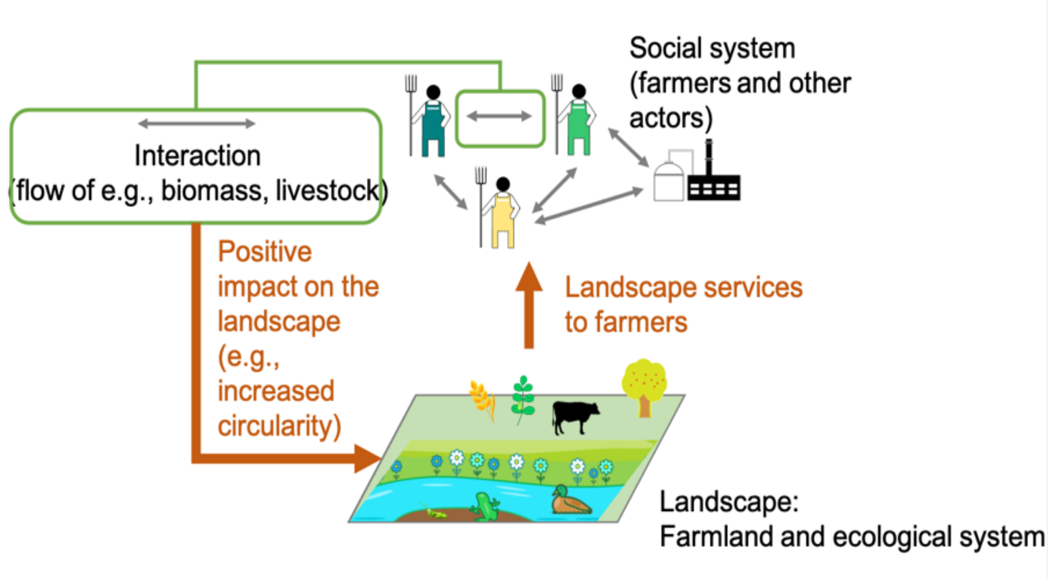

Figure 1. Within a landscape, actors (forming the social system) interact within an ecological system.

An interactions among two actors (actor 1 and actor 2) is defined as an exchange of goods (from actor 1 to actor 2 and vice versa). This exchange leads to landscape benefits, including ecosystem services, decreased imports, and nutrient recycling.

2.2 Overview of the methodologies used in the deliverable

The different methods implemented in this deliverable for studying mixedness reflect the diversity of information that can be derived from the networks in relation to the interactions occurring within landscape. We have implemented a two-tiered approach. The first step involved a qualitative analysis of all interactions (including the characterisation of the interactions and the reasons for interacting) and the second was the development of an agent-based simulation to assess manure-feed exchanges (see Table 1). The qualitative analysis created an inventory of the interactions occurring in the networks involved in WP3, giving an overview of the diversity of the types of interactions, motivations, levers and barriers. However, this does not make the interactions to be quantified possible scenarios to be assessed. In addition, we have developed an agent-based model to quantify the exchanges of manure and feed between farms in the landscapes. The farms are nodes and exchanges are connections. This formalization makes it possible to explore the role of connectivity, practices, resource availability and spatial distances on the resilience and performances of a network However, this framework does not allow us to gain insights about the diversity of interactions occurring in mixed landscapes or about the motivations behind them.

Table 1. Methodologies involved in the study of interactions

Analysis / Method	Qualitative analysis of types of farmer interactions	Qualitative analysis of reasons for farmer interactions assessed with the Q-methodology	Agent-based model
Types of interactions addressed	Potentially all types of interactions	• Feed – manure exchanges	• Feed – manure exchanges
Research questions	• How can different types of interactions be characterised? • Which is the diversity of interaction occurring in the networks involved in WP3? • Which are the barriers and levers hampering or enabling interactions?	• Which are the main reasons why farmers interact?	• How can be implemented rule-based decisions in the model, using the qualitative analysis results? • How are different types of networks resilient to different types of perturbances regarding connections?
Landscape services investigated	• Potentially all types of services	[this analysis was not addressed to landscape services but only to the reasons for farmers interactions]	• Farm and network performances concerning to resilience
Case studies involved	FR, UK, RO, PT, DK, NL	FR	FR

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3 Qualitative analysis of interactions

Author contribution statement: main contributors F. Accatino, M. Grillot and inputs from collaborators involved in the reflections and case study facilitators (Tommy Dalgaard, Camelia Gavrilescu, Jacqueline Leonte, Miranda Meuwissen, João Pedro Oliveira, Carolina Ramos, Joana Marinheiro, Cláudia Marques dos Santos, Asbjørn Mølmer Sahlholdt, Kairsty Topp, Marie Trydeman Knudsen, Monica Tudor, Christine Watson, Fergus Younger)

The purpose of this qualitative analysis is to provide insights into the different types of interaction occurring within agricultural landscapes. These interactions vary widely in type and format (Asai et al., 2018), especially across diverse European mixed farming systems, and do not always lead to integration and nutrient circularity. This section aims to: i) formalise, according the framework depicted in Figure 1, the different attributes characterising an interaction; ii) use this formalism to describe and classify the interactions occurring within the networks of WP3 in the MIXED project; iii) discuss the various levers and barriers that influence the extent and nature of these interactions at the landscape level. It is important to note that not all interactions among farmers promote landscape-level mixedness. Nonetheless, this study aims to create an inventory of all observed interactions to distinguish those that foster "mixedness" from those that do not and discuss the difference.

3.1 Formalising the attributes of an interaction

Following the scheme of Figure 1, we distinguish the elements characterising an interaction (Table 2). The first attribute is the actors involved in the exchange, where at least one must be a farmer. It is important to distinguish the type of farmer, as this highlights complementarity among farming activities. The second attribute is the goods or services flowing from one actor to another. Goods and services can be permanently exchanged (for instance, feed vs manure) or constitute temporary exchanges (for instance, livestock transported to another farm for a period of time that will for example graze over crops). Service can also include workforce (for instance, a shepherd from outside the farm taking care of a farm's sheep during transhumance). Money can also be considered in the exchange. The third element describes the benefits obtained by the two actors. These benefits include improvement in the biophysical component of the farm (e.g., improved organic matter in the soil), welfare and nutrition for animals, or a monetary benefit (e.g., increased gross margin). Although an increased gross margin might allow investments on the farm and improved condition in the biophysical system, we consider this benefit indirect and not necessarily a consequence of the interaction. The fourth element is the landscape benefit, which is the benefit obtained by the landscape as a whole (for instance, increased nitrogen autonomy of the region, reduced import of external feed, increased resilience to climate perturbation) or occurs in a part of the landscape which does not belong to the two actors involved (for instance, a communal pasture). We decided also to include all the benefit leading to improvement on the socio-economical level and improving rural vitality.

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Table 2. Attributes of interactions

Interaction attribute	Definition
Actor A	The two actors involved in the interaction.. At least one of them should be a farmer. It is important to specify the type of farmer (e.g., cereal, livestock).
Actor B	
Good or service from A to B	The goods of services flowing in the two directions (from A to B and from B to A) in the exchange.
Good or service from B to A	
Benefit for A	Monetary or non-monetary benefit obtained by the two actors. Non-monetary benefits include ecosystem services on farm (e.g., improved soil conditions) or benefits to livestock (e.g., animal welfare). Indirect benefits obtained through increased gross margin are not considered.
Benefit for B	
Landscape benefit	Benefit obtained by the landscape as a whole (e.g., increased nutrient circularity) or in a part of the landscape (e.g., a communal land) not belonging to the two actors.

3.2 The networks involved in the qualitative analysis

Six networks (details are provided in Table 3) are included in this WP3 analysis and represent a diversity of interactions within the landscape. A brief description of the networks is provided below, while more extensive descriptions are provided in D1.1 (Nicholas-Davies et al., 2021).

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Table 3. Description of the networks

Country	Short name	Description
France	FR	13 farms located in uplands (ruminants) and in lowlands (cereals) in Ariège
Portugal	PT	15 farms in the Montado (tree-grass) system in Alentejo
Romania	RO	8 small-scale farms combining mixed agricultural activities (fruit, dairy cattle, sheep) and agrotourism
Denmark	DK	11 specialised farms (pigs, dairy cattle, other cattle) and a biogas plant
UK	UK1	Winter crops and sheep farmers
	UK2	Winter crops and sheep farmers
The Netherlands	NL1	Four farms (2 mixed (dairy-arable), 1 dairy, 1 arable farm)
	NL2	Two farms (1 arable, 1 dairy)

3.2.1 France

The French system (FR) consists of the department of Ariège. The upland part of the landscape is dominated by ruminants (sheep and cattle) while the farms in the lowland mainly grow cereals. Exchanges of manure and feed occur among the ruminant and arable farms in the region.

3.2.2 Portugal

The Portuguese (PT) system consists of the Montado system in the southern region, Alentejo. It is a UNESCO protected Mediterranean agrosilvopastoral system characterized by coexistence of trees, mainly cork and holm oaks, and grass. Such system allows agroforestry and extensive livestock production. Livestock systems (mainly beef cattle, sheep, goats, pigs) are characterized by low stocking rates. Soils are mostly poor.

3.2.3 Romania

The Romanian (RO) system consists of a set of mixed farms located in an high hills and pre-mountain area in Argeş county with fruit growing activities (mainly fruit trees and berries), animal husbandry (cows and sheep), fodder production from pastures and natural hayfields. Some farms also process their farm products converting them into dairy products and practice agrotourism. The economic development of the region is therefore sustained by this activity.

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3.2.4 Denmark

The Danish (DK) system is located in the inner area of the Limfjorden. The farms are specialized farms (mainly intensive livestock) and exchange manure with a biogas plant. Surplus nutrients and losses to the environment (especially nitrogen) are a critical problem. The biogas plant is an important mediator for nitrogen redistribution.

3.2.5 UK

The British (UK) system involves two networks including arable and sheep farmers. The system consists of two types of exchange between arable farms and livestock farms. UK1/1 and UK2 involved the movement of sheep from a livestock farm to an arable farm over the winter period. The arable farmers are either growing cover crops over the winter period or are growing winter cereals. The sheep from the livestock farms graze the winter cover crops or the winter cereals over the winter period. This provides high quality forage for the sheep during the period when there is little or no grass on the livestock farm. The UK1/2 farms were exchanging manure for straw.

3.2.6 The Netherlands

The Dutch (NL) system is in the Veenkoloniën region, in the Northeast of the Netherlands. There are multiple farming activities in the region. The main need of the farmers in the region is to locally close the nutrient cycle and make improvements to the crop rotation. This requires cooperation between dairy and arable farmers as well as among arable farmers for land exchanges. Starch potato is the most profitable crop in the region, however tight crop rotations increase the risk of plant parasitic nematodes. Specifically, in this case study, there are two sub-networks studied: the first (NL-1) consists of four farms (2 mixed farms with dairy and arable farming, one dairy farm and one farm with arable and poultry farming); the second (NL-2) consists of two farms (one arable and one dairy farm).

3.3 Methodology for the qualitative analysis

In each of the networks, a common set of questions were addressed regarding farmers interactions. The method used to collect the information differed between the networks. The data was collected from focus groups (PT, RO), focus groups integrated with expert knowledge (UK, NL), by data analysis and expert knowledge (DK), or with a series of in-depth farmers interviews (FR). Case study facilitators were asked to harmonize the information collected from each of the networks. The first table (Table 4) consisted of describing the interactions following the attributes given in Table 3. The second table (Table 5) consisted of a set of factors that could be considered levers or barriers for the occurrence of interactions among farmers. Networks facilitators were asked to indicate the factors that they considered present in their network. All the interactions were collected, therefore also those not leading to "mixedness" at the level of

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farm or landscape. Further reflections were dedicated to qualify those interactions leading to improved landscape mixedness.

3.4 Results of the qualitative analysis

3.4.1 Inventory of interactions

Interactions were assigned an ID, described and classified in Table 4.

3.4.1.1 France

Ruminant farmers from the uplands provide manure to the cereal farmers in the lowlands and receive forage.

3.4.1.2 Portugal

Two interactions were observed in the Portuguese networks. In the first interaction (PT-1/1) pigs are sent to the Montado from outside the farm and stay there for about 4 months, as a final fattening stage, feeding mainly on acorns. The pigs help by turning over the soil and leaving their dejects for the pasture and trees. This service is 100% paid by the pig farmers based on the pig's weight gain. In the second interaction (PT-1/2), sheep, apart from grazing in the Montado, are brought to graze into certain parcels of other farms such as vineyards or olive orchards. This decreases the need of machinery to control bushes and weeds and, at the same time, provides feed for the sheep. In some cases, goats involved, although they require more management to ensure that they do not destroy the crop.

3.4.1.3 Romania

Three interactions were observed in the Romanian case study. In the first interaction (RO-1/1) sheep are sent with a shepherd to mountain pastures from the spring to the autumn. This constitutes a traditional transhumance practice. In the second interaction (RO-1/2), dairy products are exchanged between dairy and sheep farmers and farmers with agrotourism facilities, therefore helping each other economically and help with the development of agrotourism in the region which creates jobs locally. Because all the farms are already mixed, the exchanges are mostly for products they themselves do not produce. This exchange promotes diversification at the landscape scale.

3.4.1.4 Denmark

Farmers send their manure to the biogas plant and receive digestate (DK-1/1). Some farms pay for receiving more digestate than equivalent to the manure they sent: this leads to indirect interactions among farmers mediated by the biogas plant, leading to a nitrogen re-distribution in the region, reducing the need for synthetic fertilizer.

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3.4.1.5 UK

Exchanges in the UK network involve livestock being moved over the winter period to arable farms to graze either cover crops or winter cereals (UK-1/1, UK-2/1). The second type of exchange occurring in the UK network (UK-1/2) is manure for straw deals.

3.4.1.6 The Netherlands

The arable and dairy farmers exchange land parcels in order to optimize rotations and therefore increase their productivity (NL-1/1). In the objective of the exchange is to maintain a high level of productivity while at the same time respecting the planting and harvesting, and disease restrictions needed for the rotations. The dairy and arable farmers exchange manure for feed (NL-2/1).

3.4.2 Overall summary of the interactions observed

The interactions observed are classified in Table 4 following the overall attributes given by the framework in Figure 1 and
Table 2.

Table 4. Inventory of the observed interactions and their attributes.

The benefits and services are only qualitative and their effective contribute can be assessed only through quantification. All the interactions were included in the inventory, also those not leading to increased "mixedness"

ID	Actor A	Actor B	Good or service from A to B	Good or service from B to A	Benefit for A	Benefit for B	Landscape service
FR-1/1	Ruminant farmer	Cereal farmer	Manure	Forage, straw	Forage for animals	Improved soil fertility, reduced dependency on mineral fertilizer	Nutrient circularity in the region
PT-1/1	Montado farmer	Pig farmer (from outside the network)	Acorns	Pigs, money	Gross margin, improved pasture conditions	Improved animal welfare, feed of better quality	Improved nutrient circularity Soil enrichment by pig dejects

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ID	Actor A	Actor B	Good or service from A to B	Good or service from B to A	Benefit for A	Benefit for B	Landscape service
PT-1/2	Orchard/vineyard farmer	Sheep farmer	Grazing area	Sheep, money	Gross margin, weed control	Forage for animals, improved animal welfare, additional feed availability	Improved nutrient circularity Soil enrichment by sheep dejects
RO-1/1	Farmer	Shepherd	Money, products	Specialized work	Animal welfare, improved feed for sheep	Gross margin, cheese	Pasture maintenance
RO-1/2	Farmer or farmer with and agrotourism facility	Farmer or farmer with and agrotourism facility	Dairy products, fruit, manure, calves, money	Dairy products, fruit, manure, calves,, money	Improved variety of services, self-sustainment	Improved variety of services, self-sustainment	Agro-tourism development in the region, employment creation
RO-1/3	Farmer	Processing industry	Fruits	Money	Gross margin	Fruits	Agro-tourism development in the region, employment creation
DK-1/1	Specialized pig or dairy farm	Biogas plant	Manure, Money	Digestate	Reduced synthetic fertilizer, improved soil conditions, indirect re-distribution of surplus organic nitrogen	Gross margin	Improved nutrient circularity, higher nutrient efficiency and gross margin

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ID	Actor A	Actor B	Good or service from A to B	Good or service from B to A	Benefit for A	Benefit for B	Landscape service
UK-1/1	Sheep farmer	Arable farmer	Ruminants	Winter cereals / cover crops	Animal welfare, reduced need of buying feed	Improved soil organic matter / soil health, reduced potential to reduce plant disease in winter cereals, money	Improved nutrient circularity
UK-1/2	Sheep/beef farmer	Arable farmer	Manure	Straw	Reduced need of buying straw	Improved soil organic matter / soil health, reduced dependency on synthetic fertilizer	Improved nutrient circularity
UK-2/1	Sheep farmer	Arable farmer	Ruminants	Winter cereals / cover crops	Animal welfare, reduced need of buying feed	Pasture maintenance, improved soil organic matter	Improved nutrient circularity
NL-1/1	Arable farmer	Arable farmer	Land	Land	Improved rotation and production of more rentable crops	Improved rotation and production of more rentable crops	Increased production in the respect of the rotations?
NL-2/1	Dairy farmer	Arable farmer	Manure	Feed	Improved soil fertility, Reduced dependency on mineral fertilizer	Feed for animals	Nutrient circularity in the region, reduced imports of feed/manure

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From the above, different types of interaction can be observed:

- A first set of interaction (*feed/straw-vs-manure*) consisted of exchanges between specialised crop and specialised livestock farmers (FR-1/1, UK-1/2, NL-2/1). This interaction takes advantage of farm complementarity and helps the region's self-sufficiency in manure, feed and straw, reducing the needs of importations and improving the local closure of the nutrient cycle.
- A second set of interactions involved transferring of livestock (*livestock-transfer*) from one place to another for a certain period to satisfy dietary needs and needs related to crop/orchard cultivation. In PT-1/1, pigs benefit from a diet based on acorns and improve Montado soils; in PT-1/2, sheep benefit from having swards to graze, and they also help to control weeds; in RO-1/1 sheep benefit from having grassland to graze on the mountain and they contribute to the maintenance of a pasture in the landscape (communal land). This practice also contributes to job creation as specialized workforce is needed. In UK-1/2 and UK2, sheep are grazed on winter cover crops or winter cereals and benefit from improved nutrition.
- The other types of interactions involve only one interaction and are therefore more specific. In DK-1/1, the biogas plant acts as a mediator allowing an indirect nitrogen redistribution. In NL-1/1, the land parcel exchange allows for optimized rotation, focusing on increased food production and reducing the risk of pathogen attack. In Romania, the interactions are focused on economic development, and do not improve the biological efficiency of the farms. For example, in RO-1/2, dairy products are exchanged between farms. The interaction in RO-1/3 is between the farmers and an external industry. Both these interactions support the local economy and provides financial reward to the farmers.

3.4.3 Barriers and levers for interactions

Table 5 shows the main factors (levers and barriers) to interaction development noted in the networks (not implemented by NL). Factors were classified according to whether they originate from outside (external) or from within (internal) the farm. Among the external factors, the most indicated lever was "increased quality and/or production diversification", showing that productivity purposes (production maximisation, diversification, and quality) is a main driver for collaboration. This is also the case for NL where farmers exchange land to improve everyone's productivity. Other external factors that were mentioned by the networks were the integration of farmers in a local network, and willingness to develop new business partnership, while a barrier was the conflicting relationship with partners. This suggests that relationships among farmers are key for the interactions to take place. Among the external factors, climate change was mentioned as a barrier which reduces productivity and therefore reduces the availability of goods to exchange; cheaper home-produced goods were mentioned as lever; regarding policy, rules limiting farmers' sales were considered to be strong barriers.

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Table 5. Barriers (-) and levers (+) for the development of interactions among farmers.

Source	Category	Negative (-) and positive (+) factors		Networks
INTERNAL	Personal preferences	-	Integration in a cooperative	
		+	Integration in the local network of farms	UK, PT
	Land	-	Increased autonomy; reduced need for exchange with other farms	
		+	Increased quality and/or production diversification	PT, DK, RO
	Labour force	-	Simpler activities	UK
		+	Increase diversification and/or increase of production	RO
	Human relationships	-	Conflictual relationships between partners	DK
		+	Contact with new business partners	UK, DK
EXTERNAL	Climate	-	Reduced supply	RO, UK
		+	Increased demand	
	Market prices	-	Substitution with cheaper products	
		+	Home-made products are cheaper	RO, UK
	Policy	-	-Regulations (rules, norms, taxes) which limit the sales	DK, PT, RO
		+	Conversion support/subsidies --> new products	UK

3.5 Discussion of the qualitative analysis

Observed interactions are here discussed under the point of view of the closure of nutrient cycle and resilience (Table 6). Where possible, interactions are grouped in types (*feed/straw-vs-manure* and *livestock-transfer*), otherwise they are considered singularly. For sure, quantitative information about the interactions (e.g., how much feed-manure is exchanged) is necessary for complementing the analysis. However, the discussion can be still done in principle based on the qualitative information.

3.5.1 Closure of the nutrient cycle

In principle, the closure of the nutrient cycle can be improved in the *feed/straw-vs-manure* and in the *animal-transfer* interaction types. However, it depends on the distance at which the interaction occurs. In particular, among the interactions analysed, PT-1/1 and PT-1/2 involve animals transferred from outside the study network, and RO-1/1 involves the long-distance transfer of sheep to the mountains, which poses questions about nutrient transfer among areas.

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Overall, the notion of "closure of nutrient cycle" depends on the boundary of the area considered. Concerning the RO-1/2 interaction, the exchange occurs on the economic layer of the landscape, therefore not guaranteeing any circularity in nutrients. Concerning DK-1/1, the transfer of manure and digestate is agreed by an individual farmer with the biogas plant. Therefore, although balancing the nutrients is theoretically possible, it would require regulation and co-ordination between farmers to be achieved. NL-1/1 does not guarantee in principle nutrient balance, as the interactions involve exchanges of land and not nutrients.

3.5.2 Considerations about resilience

Resilience is considered the capacity of the system to deliver public and private goods despite challenges and stressors (Meuwissen et al., 2019). For a more detailed definition of resilience, it is necessary to specify "resilience to what" (Carpenter et al., 2001). However, following Cabell and Oelofse (2012) it is also possible to consider a "generic resilience" following some criteria that make a system overall more resistant to generic perturbations. In feed/straw-vs-manure exchange the nutrient self-sufficiency of the region is protected if there is a solid network of exchanges among farmers. Conditions for the resilience of a network are discussed with the modelling approach (Chapter 5). In general, all the interactions (except DK-1/1) rely on continuous partnership. Concerning DK-1/1, the efficiency of the network relies too much on the price set by the biogas plant, raising concerns about the resilience.

Table 6. Considerations about the types of interactions

Criterion for discussion	**feed/straw-vs-manure**	**livestock-transfer**	**RO-1/2**	**DK-1/1**	**NL-1/1**
Improvement of the closure of nutrient cycle	Yes, depending on the distance of the exchange	Yes, depending on the distance of the transfer	Not necessarily, as exchanges focus on the products and not nutrients	Yes, but it should be regulated	No, as there is no nutrient movement
Considerations about resilience	See Chapter 5 for the conditions of network resilience. Importance to have continuous partnership for the exchanges	Importance to have continuous partnership for the exchanges	Importance to have continuous partnership for the exchanges	Resilience of the network is weak as it depends on the behaviour of a central economic actor (prices determined	Importance to have continuous partnership for the exchanges

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				by the biogas plant).	

3.5.3 General considerations

In some case studies, some general considerations about interactions and policy implications were done and are here summarized. Most of the interactions examined are bilateral and typically characterised by mutual trust and good relationships, with some instances involving the sharing of resources incl. specialised labour. None of these interactions are governed by legal agreements; they are informal and often overlooked by policy-makers for this reason. Policies might recognise and value the interactions among farmers rather than focusing solely on individual farms. In the context of MIXED, facilitating the development of good relationships between farmers is crucial and can be supported through intermediaries or cooperatives. In the DK network, integration into a cooperative enhances indirect interactions among farmers, making the intermediary role of the biogas plant beneficial. In FR and the UK, advisors already contribute by organizing training for crop-livestock interactions and serving as intermediaries. NL farmers have expressed the need for advisors skilled in fostering interactions among farmers rather than specialising solely in crop or dairy farming. These bilateral relationships could also be safeguarded through formal agreements.

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4 Identifying main influencing decision-making factors to interact with other farms

Author contribution statement: M. Grillot and C. Triolet.

In the previous section, we described the interactions, including some considerations among their characteristics, the main levers and barriers, and some overall considerations in relation to "mixedness" and some policy implication. However, we did not describe in detail the factors underlying the behaviour to interact. Asai et al. (2018) highlighted factors that are important in assessing how farmers interact. These included a variety of operational costs, availability of on-farm storage capacity and transportation, geographic distance and legal aspects related to contracts and billing. They also showed that establishing trust and shared goals, and the complexity of governance were also impacting factors. From that result, we assumed that social networks and social factors are key to more or less interactions among farms. In addition, as highlighted by Bouttes et al. (2019), farmers do not only focus on financial aspects and/or optimized productivity. Each farmer has his/her own objectives depending not only on farm structure but also, on individual values. Following economic theories, we also embrace the assumption that farmers face bounded rationality, *i.e.* they do not always make optimal decisions as they have a limited perception of their environment. In the following section we dive into decision factors that are beneath these interactions. As this part requires a handful of specialized data on farm, we conducted this additional exploration only in the Ariège case study. We decided to work on factors, levers and barriers related to existing situations where farmers already had a will to interact, in order to encourage it.

4.1 Methodology

4.1.1 General approach for semi-structured interviews

To the purpose of this additional exploration, we developed a survey protocol to conduct semi-structured interviews with farmers in the French (Ariège) case-study. The interviews aimed at providing in-depth information on farmers interactions and, when possible of their changes over time. We aimed for a diversity of farmers (crop, mixed, livestock farmers). We first selected farmers from a group engaged in a participative process since 2017 aiming at more interactions between farms. The farmers we reached were willing to share their experiences but did not have much time and information could be fuzzy on past interactions when not known. As some knowledge was already available on past interactions, our aim was to shorten the time of questions on farm structure and past interactions and save time to discuss about the evolution of interactions. We contacted other farmers by snowball effect. We also endeavoured to contact farmers who had stopped interactions or were not willing to start some but could not reach them.

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The study sample consisted of 13 farmers: 5 crop farmers, 4 mixed farmers and 4 livestock farmers. Nine farmers were contacted from the group (4 crop farmers, 3 livestock farmers and 2 mixed farmer) and four by snowball effect of the first interviews (1 crop farmers, 1 livestock farmer and 2 mixed farmer). The latter four provided the partner's point of view on interactions already discussed. Our sample was representative of the members of this group engaged in discussions for more interactions with other farms.

We interviewed the farmers face-to-face in 2022 for an average duration of 1h30-2hours per interview. The interview guide was the same for all farmers (see appendix B). Topics were different depending on the productions (e.g., selling price of the crops with crop farmers, price of feed with livestock farmers). Each interview had three parts. The first part dealt with the interactions carried out, based on the 2017 or 2020 flow chart, if existing (see appendix C). We used this time to correct and validate this network of interaction. Then the interviewee was invited to update the flow chart for year 2021 or, if not existing, to create it. We discussed on the use of agricultural products and co-products of the farm, and when relevant, about the partners involved in the interaction. Structure of the farm related to these usages and evolutions were also discussed. For each interaction, motivations, characteristics of the partner, modalities of interactions, duration of the interaction and the elements that may have triggered the end of it were also discussed. The second part of the interview dealt with the resilience of the system to climatic and economic hazards, particularly how these external factors influenced their strategic and operational decisions. At the third and last part, the interviewee classified 17 factor-oriented statements related to four themes, describing actions that could influence interactions related to biomass flows (Q method, see below). An influencing factor is a characteristic of the interaction that will have more or less weight in the final decision to engage or not in the interaction.

4.1.2 Focus on the Q method

The Q method is appropriate for small samples of interviewees and to highlight perceptions and prioritization of the influencing factors (Dieteren et al., 2023; van Dijk et al., 2022; Dziopa and Ahern, 2011). We focused on factors that would influence interactions between farmers, whatever their specialisation, aiming to define typical sets of common decision-making factors. We first identified factors that seem important for the farmers before engaging or not in an interaction, based on literature and previous interviews. We mostly used data from articles of Asai et al. (2018, 2014a, 2014a) and Martin et al (2016) and previous interviews with farmers in Ariège. We identified four themes that often contribute to the establishment and sustainability of an interaction: agronomy, economy, logistics and relation & solidarity. We translated them into 17 statements that would require a closed answer (Table 7). Interviewees rank and classified all 17 statements within a given matrix (Figure 2) scaling horizontally from "it's very important to me" to "it's not important at all". All statements had the same value vertically. The ranking referred to a specific interaction (biomass against straw, mown fodder, grazed fodder, grain or manure). If an interviewee was involved, had been involved, or had plans to be involved

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in a specific interaction, we would ask the farmer to do the classification. Interactions could therefore be hypothetical or actually carried out. For instance, for a crop farmer who had stopped straw-manure interaction, we would specifically ask him/her to classify the statements for this interaction, by the time he/she was engaged in it. If a farmer was engaged in more than one interaction, we would ask him/her to make a classification for each interaction. Each classification resulted in what we call a Q-sort.

Table 7. Theme and associated statements used in the Q method

Theme	Statements
Agronomy	It provides me with an agronomic service (contribution of organic matter, destruction of cover crops). It allows me to be less dependent on cooperatives. The contact person has the technical knowledge to assure me of good quality.
Economy	This is the best price on the market today. A stable price is set for several years. It's a give and take.
Logistic	The distance to be covered is small. The logistical cost is low. We have a written contract. We have an oral contract. We have agreed on a timetable which will be respected. We can be flexible and arrange the dates. We can be flexible and make arrangements on quantities.
Relation & Solidarity	I trust the person I'm talking to, he will respect his commitments. I can easily contact him. It is to be of service (solidarity). I help him when he needs it, he helps me when I need it.

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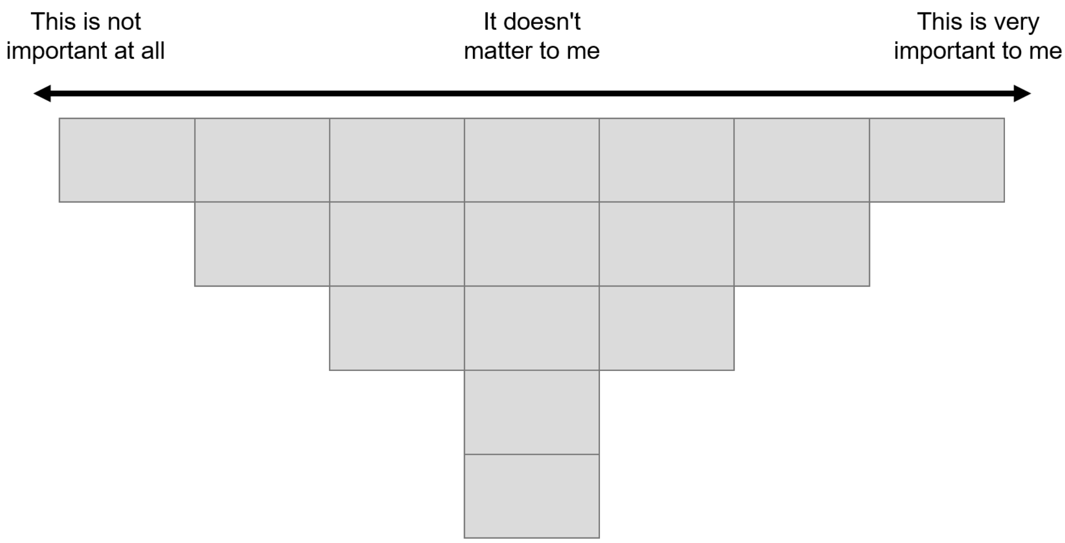

Ranking	- 3	- 2	- 1	0	1	2	3
Number of card	1	2	3	5	3	2	1

Figure 2. Matrix for the Q-method to classify the 17 statements

For each Q-sort, we associated the statement with its ranking (see Figure 2). We used the qmethod[1] package on the R software2 in order to establish groups of common factors that were used for each type of interaction (being the most and/or least important).

4.2 Description of the interactions and important influencing factors mentioned

The following results were presented at International Farming System Association (IFSA) conference 2024 in Trapani (Italy). For season 2021-2022, over 13 farms, two farms were not involved into any interaction: a crop farmer sold all his grain to the cooperative and kept his straw as mulch and a mixed farmer was fully autonomous. For the 11 other farms, we recorded 51 interactions in total. On average, there were four interactions per farm (range: 1 to 8 interactions) and three different partners per farm (range: 1 to 6 partners). Nine pairs of farms interacted for more than one type of biomass. Most of the interactions occurred between farmers with a spatial proximity (45% with neighbours), or social proximity (31% with friends or family), while 23% occurred with an acquaintance from the professional network. Farmers sealed an oral contract in 75%, none in 23% and a formal contract in 2% (1 case) of the interactions. The formal contract concerned a crop farmer and a livestock farmer who met through their professional network. They mainly established it to cover for insurance as the interaction involved sheep grazing within the crop farmer's farm. Oral contracts varied in

[1] Aiora Zabala. qmethod: A Package to Explore Human Perspectives Using Q Methodology. The R Journal, 6(2):163-173, Dec 2014

[2] R Core Team (2024). _R: A Language and Environment for Statistical Computing_. R Foundation for Statistical Computing, Vienna, Austria. <https://www.R-project.org/>.

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substance but specific terms could be agreed upon, such as date of removal (e.g. take away the straw from the field as soon as it is packed and ready).

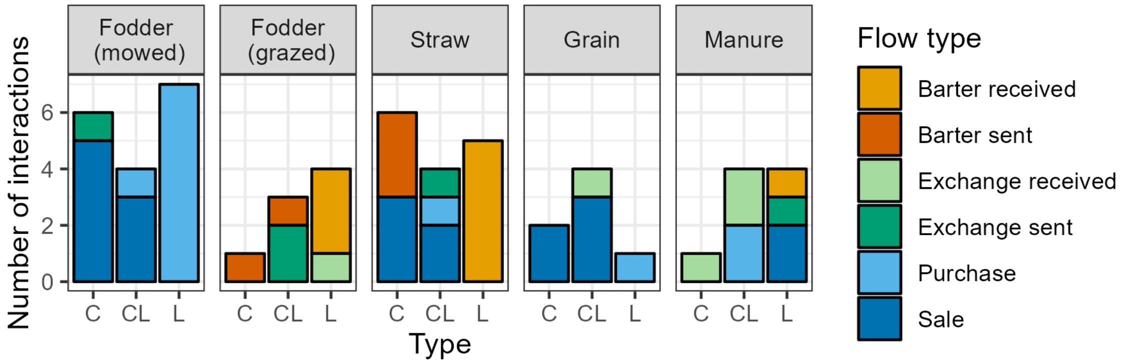

Figure 3. Interactions from 2021 to 2022 by biomass, flow type and type of farmer
C = crop farmer, CL = crop-livestock farmer, L = livestock farmer.
Exchange flows were recorded twice (received and sent)

Interactions involving fodder were the most common (25 interactions, or 44%, Figure 3). They involved both crop farmers who supplied the biomass and livestock farmers who sought it. Mixed farmers were buyers when their own production was insufficient and sellers when they produced surplus. Overall, 64% of fodder-related interactions involved buying and selling. Over the years, new interactions with cover crop and cereal grazing were tested and adopted. Fifteen interactions involved straw (27%, Figure 3). They were mainly bartering (53%), followed by buying and selling (40%) and exchange for manure (7%). As with fodder, mixed farmers were both buyers and sellers. Nine interactions involved manure (17%, Figure 3). There was as much buying and selling (45%) as exchanges for straw or grazing (45%) and one donation (10%). Seven interactions involved grain (12%), of which 86% were buying and selling, and 14% were exchanged (Figure 3). In terms of quantity, these interactions represented a small amount of crop total production, most of the grain was sold to cooperatives.

Even though farmers did not seal written contracts with each other, they agreed upon modalities and rules for their collaboration. They wanted to keep these collaborations based on trust and flexibility through the years. Long debates arose when mentioning the possibility to prepare a contract with fixed prices in order to cope with price volatility. One crop farmer even mentioned the need for a neutral institution to help set up mechanisms to decide prices with a fair adjustment through years.

4.3 Results on main influencing factors

As a confirmation to what the farmers had expressed when mentioning important barriers to interactions between farms, logistics and costs were important decision factors for all biomasses. However, their perceived level of importance on the choice to whether or not involve into interaction depended on whom was in charge of it. Most of the straw and mowed fodder were handled by the receiver (livestock owner) and did not affect the crop farmers, as long as it was collected right after the harvest to let them time to prepare for the next crop. It

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was more heterogeneous for interactions involving grain (even though even availability of storage was important factor in the arrangement).

Based on the interviews, we noted tensions around straw and manure. Most farmers had stopped straw-manure exchanges due to high logistic costs and straw sales without manure in return left a feeling to downgrade from a win-win to a loose-win situation (in favour for the livestock owner; crop farmer: "*There really has to be an agronomic balance. As far as I'm concerned, what you take from the soil, you have to give back.*"). Crop farmers tended to keep straw in the fields to improve or maintain soil quality ("*if I sell my straw [without manure in return], I need mineral fertilizer to compensate and this is not my wish*"). Main factor to maintain straw-manure exchanges was solidarity, related to trust and friendship. This was the same for straw sales ("*In solidarity with a livestock farmer, I give him straw. Actually I don't give it, I sell it but at a reasonable price*").

Specifically, results from the q-sort analysis, we highlight the following groups of decision-factors. The type of biomass and not type of the farmer led to different decision-making priorities.

- For fodder, three groups emerged. These groups overlapped on common concepts: logistics was important for all three, quality control and the economy was important for two groups together (F1 and F2), while the last group emphasised fairness (F3).
- For straw, four groups emerged, focused on quality (S1), the economy (S2), relationships (S3) and logistics (S4), respectively.
- For grain, four heterogeneous groups emerged, with emphasis on relationships (G1), the economy (G3) and quality control (G4). G2 emphasised social, economic and agronomic aspects.
- For manure, three groups emerged. They overlapped on the concept of logistics, with a strong desire to decrease costs, particularly M2. M1 and M3 emphasised the fairness of the partnership, while M3 emphasised a desire to be independent from the cooperative.

4.3.1 Fodder

Over 9 q-sorts, we highlighted three groups (Figure 4). Group F1 "price-quality ratio" (blue group, n=3) emphasises on quality – "the partner's technical knowledge ensures good quality" - and the profitability of the interaction – "the best market price" and "the short distance". This is a group of livestock farmers who buy fodder. In their discourse, feed quality was seen as paramount.

Group F2 "economics" (green group, n=3) focuses on agreements between farmers and the profitability of the interaction. The "oral contract" is the most important factor, followed by "best market price" and "independence from the cooperative". Crop farmers selling fodder make up the group.

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Group F3 “balanced and low-distance” (orange group, n=3) emphasises on the practicality of the “short distance to travel”, the security of the “written contract” and the balance of the relationship – “give and take”. A livestock farmer and mixed farmers make up the group.

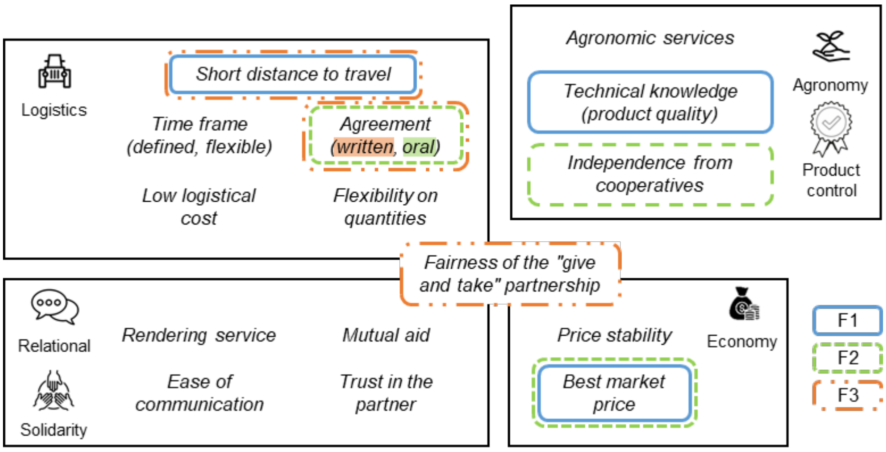

Figure 4. Groups of factors identified by the analysis of q-sorts on interactions related to fodder

4.3.2 Straw

Over 11 q-sorts, we highlighted four groups (Figure 5). Group S1 “solidarity and agronomy” (blue group, n=3) emphasises the solidarity nature of the relationship, the trust in the interlocutor and the agronomic service provided by the manure compensation, often carried out in return. The most important factors are "service rendered", "trust" and "agronomic service". The least important factors are “best price” and logistics. The formal aspect of the interaction is not very important. Crop farmers and mixed farmers compose the group.

Group S2 “economy and relational” (green group, n=2) emphasises the cheapness of the biomass and the reliability of the partner in the interaction. The most important factors are “best price”, “price stability” and “trust in the partner's commitment”. The least important points are the establishment of a “written contract”, “solidarity”, and “technical qualities that ensure quality”. This group includes livestock farmers only who buy standing straw.

Group S3 “solidarity and balance of the relationship” (orange group, n=3) also emphasises the solidarity aspect of the interaction – “rendering service” being the most important - and the service rendered in return – “give and take” - generally through the provision of manure. This group includes both crop farmers and livestock farmers who mention the mutual benefit of the relationship in their discourse.

Group S4 “economy and logistic” (purple group, n=3) emphasises on the logistical aspect of the interaction. The low cost of the interaction for the biomass supplier is important. The important factors are “low logistical cost”, “short distance” and “respect for interaction dates”. This group consists of crop farmers only.

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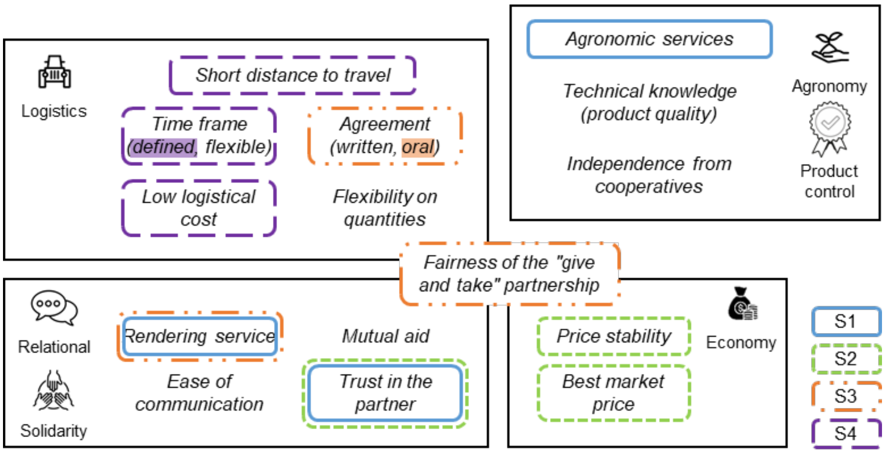

Figure 5. Groups of factors identified by the analysis of q-sorts on interactions related to straw

4.3.3 Grain

Over 9 q-sorts, we highlighted four groups (Figure 6). Group G1 “solidarity” (blue group, n=3) recognises the importance of the “oral contract” in the relationship, as well as the trust and help provided, as important, and the more economic and agronomic side as not important. These are mainly crop farmers who have been involved in direct grain sales for a long time.

Group G2 “stability, agronomy and solidarity” (green group, n=2) is a heterogeneous profile that pays attention to "price stability", "agricultural service rendered" and "mutual aid". The balance of the relationship and the structural organisation of the interaction are not important. Crop farmers with some direct grain sales and mixed farmers make up the group.

Group 3 “economy” (orange group, n=2) pays attention to the financial and temporal costs of transporting the interaction - "short distance" - and to the profitability of direct sales - "best market price" and "fixed price" -. Solidarity and agronomic services are of little importance. This profile includes crop farmer and mixed farmer, both of whom sell grain.

Group G4 “autonomy” (purple group, n=2) admits a dimension of autonomy – “less dependent on cooperatives”. The focus is on the skills of the interlocutor and on the trust involved. The "mutual aid" and "best market price" aspects are less important. Livestock farmers in this group have autonomy objectives and a project to manufacture feed on the farm.

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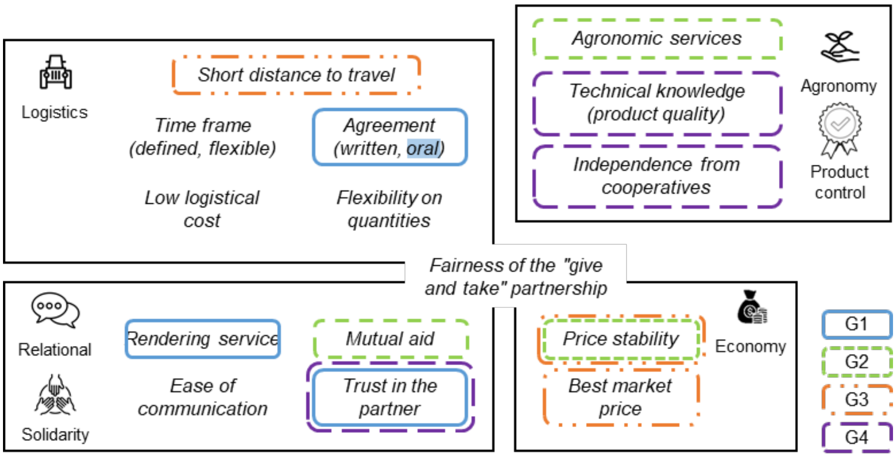

Figure 6. Groups of factors identified by the analysis of q-sorts on interactions related to grain

4.3.4 Manure

Over 6 q-sorts, we highlighted three groups (Figure 7Figure 6). Group M1 “balanced and low distance” (blue group, n=3) emphasises on the low cost of the manure movement, with "short distance" and "low logistical costs", and also the balanced character of the interaction with "give and take". The solidarity aspect was not considered important. The crop farmers in the group would be willing to collect manure from a livestock farmer and spread it on their plots.

Group M2 “reliability and low distance” (green group, n=2) also emphasises on the low cost of the interaction – “short distance” and “low logistical costs” - but also on the importance to secure the interaction through the establishment of a “written contract”. Price aspect is not important. Indeed, livestock farmers who donate or would donate their manure would not sell it. They also do not want to bear the cost of transport.

Group M3 “trust and autonomy” (orange group, n=1) emphasises on the trust and balance within the relationship– “oral contract” and “give and take” - and on the autonomy provided by the exchange against straw – “less dependent on cooperatives”. The price and distance aspects are not taken into account, as the livestock farmer in this group gives his manure to a crop farmer who bears the logistical cost.

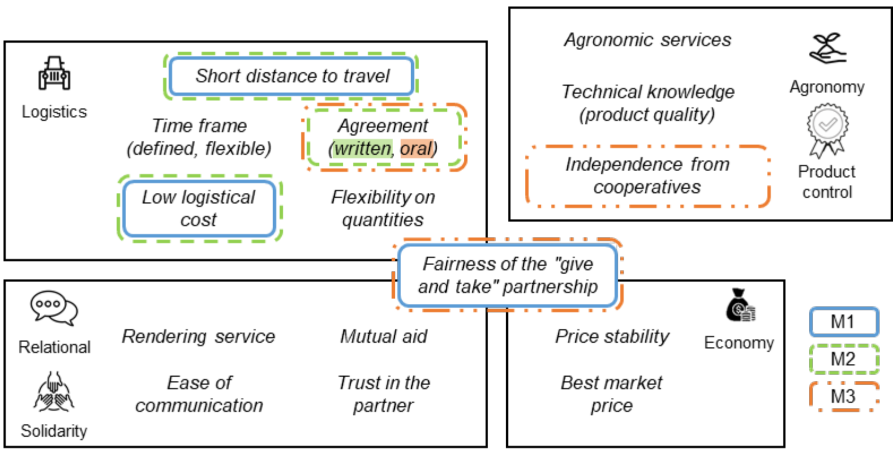

Figure 7. Groups of factors identified by the analysis of q-sorts on interactions related to manure

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4.4 Discussion and implications of the main results on decision factors for interactions

4.4.1 Few elements on the method

We conducted face-to-face interviews based on the network of interaction of the farmers. This method is classical for network analysis but original in the way we used it as an entry point to discuss decision factors for interactions. It allowed to capture the "full" network of interaction of the farmers, even though it may omit some (most often because they forget to mention it). By incrementing this network physically on a paper along the discussion we could address and visualize them. We adapted the Q-method to wrap-up the discussion we had with the farmers, at the end of the interviews. We argue that using it at the end of the interview allows the farmer to dive into the mechanisms of interaction before reflecting on the ranking of influencing factors. However, as we aimed to work on a diversity of interactions that were not all implemented by the farmers we interviewed, the number of q-sort varied between interaction types (from 6 to 11), which is a potential limitation. More interviews would ensure a higher robustness or confidence, as we could check whether the groups remain stable or not. At the same time, the number of resulting q-sort has allowed to observe that while most farmers mentioned straw-manure interactions, only a few farmers would practice it.

Another limitation might be the fact that no more than one person related to the farm manager was interviewed in each farm, mainly due to that fact they could not spare time for two multiple interviews within the farm. In cases where multiple persons manage one farm, it could have been interesting to propose the ranking of factors to the different partners, potentially highlighting certain dissonant visions or providing new insights on the interactions with other farms. This is particularly true for mixed farms where two different persons may be in charge of crop and livestock productions, making their own operational decisions. This could also have been true when partners are of different generations. According to Asai et al. (2014b), the older ones tend to give more importance to social aspects (knowledge, communication). We also noticed that in the case of a family takeover, children who may wish to implement innovations could give up in favour of the decisions of the elders, in order to avoid conflicts.

4.4.2 Highlights and implications

Logistics is a main important factor for decision-making for an interaction. It reflects distance and cost of transportation and thus its importance for the farmer depends on who takes the costs in charge. In that sense, livestock and crop farmers often have slightly different decision-factors for the same interaction, while crop-livestock farmers may switch from the position to offer or demand a product. For example, if they have a shortage of fodder, they will have a reasoning similar to that of livestock farmers in search of fodder. In the case of grain, however, they were all in the position of sellers, and therefore close to crop farmers.

In our sample, we did not have organic farmers. However, Asai et al. (2018) showed that the obligation to use organic inputs on certified farms lead farmers to be more flexible about longer

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distances, more accommodating about the terms of agreements. Indeed, as the biological resource was scarce, farmers were more willing to make concessions.

Selling/buying products from the cooperative seems to diminish the logistical cost regarding the concordance of time schedule and quantities: they always have an employee available and large quantity of products. What refrains to engaging in interactions with the cooperative is mostly related to trust on quality (for livestock farmers on livestock feed) and will for what they call local autonomy (*i.e.*, at landscape level). Despite an expressed mistrust towards cooperatives, further research could be undertaken on their role as innovation intermediaries; e.g. as conducted in China by Yang et al. (2014). We confirmed the importance to emphasize on trust and social capital, as highlighted by King et al. (2019).

Some farmers mentioned that the existence of written contract was part of their decision-making process (for fodder and manure). However, none of them but one mentioned signing them. Formal written contracts provide security in case of disagreement and clarity in the exchange to the partners by setting the terms and conditions, however they leave little room for adaptation in the face of contingencies, unless explicitly provided for in the contract. Informal contracts allow for more freedom in organisation but can lead to conflict and misunderstandings about dates, quantities and goods involved (Asai et al., 2018). The article by Asai et al (2018) makes it explicit that an informal relationship that is already present can lead to a long-term partnership formalised through a contract. What seems to be difficult is then to settle on a price with the possibility that the market changes drastically and that one of the partners loses money (compared to the external market).

Understanding farmers' perceptions and decision factors to get involved into interactions was and remains a necessary first step in supporting the development of such interactions. In the study region, but likely also in most other European regions (as shown in §3), farms do interact with other farms (through biomass, workers, machinery, etc.). However whilst they often benefit from local coexistence, they are more rarely involved in a stronger level of integration leading to more spatial, temporal and organization coordination (Martin et al., 2016). We showed that interactions between farms is not only a question of offer and demand, there is more at hand. We showed that his/her perceptions and decision factors for being involved into interactions may even differ according to the biomass considered and farmers' position (i.e. supply or demand). We showed the importance factors such as trust, solidarity, and spatial and social proximity and price stability when involving into interactions with other farms. Many interactions with neighbours relied on informal help, which is key element but rarely documented in studies. Also, there was a gradation in the interactions, as after many interactions with acquaintances from the professional network, friendships developed. This was also shown by Asai et al. (2014b) who also showed that the transaction cost of the interaction decreased over time. These long-term and strengthened interactions could also lead to more subsequent changes in the cropping systems (e.g. choice of the crop composition for fodder) and to more integration, contributing then more to the agroecological transition. These dynamic and individual elements should be thought through when developing models on farmers' decision-making, especially regarding farm interactions.

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5 Modelling farmers' interactions at landscape level: insights from an agent-based model

Author contribution statement: A. Peter and M. Grillot.

In the previous sections, we described the interactions and the decision factors that influenced them. Now, we aim at understanding the emergent network behaviour raising from the implementation of farmers interaction at the level of landscape. To that aim, we decided to build a model that could represent these interactions and simulate them at landscape level.

At the beginning of the project we worked on D3.2 (Grillot et al., 2022) where we described a first conceptual version of the model and why we chose an agent-based model to do so (diversity of individual behaviours that interact in a spatialized environment they can interact with). Since then, we built on that work in order to expand the model, implement it on a simulation platform, explore it in order to use it for simulations (Table 8). In this section we present a streamlined description of the augmented conceptual according to the Overview Design concepts and Details protocol (ODD) (Grimm et al., 2020). Then we define the system we study, corresponding to a multi-level analysis and the indicators to study them. We then show how we explored the model in order to verify the implemented mechanisms and set the initialization parameters. Lastly, we show relevant simulation results.

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Table 8. Evolution of the modelling process and agent-based model since D3.2

Model elements	**D3.2**	**D3.4 (current deliverable)**
Model purpose	Set	Unchanged
Agents	Farm, livestock, plot	Cooperative is added Stock is added to homogenize product management Livestock farmers can have sheep
Spatial and temporal unit	Region (Ariège), yearly basis	Unchanged
Processes: interactions	Algorithm: college admission problem	Improved mechanisms of trust evolution, threshold to set up the list of potential partners, possibility to choose a random partner, etc.
Crop and livestock productions	Based on expert knowledge	Fitted with regional data
Initialization data	Averaged national data	Fitted with regional data Heterogeneity within farms
Model implementation	-	Done on GAMA platform
Model verification and validation	-	See explorations (§5.3)
Model simulations	-	See simulations (§5.4)

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5.1 Model description

5.1.1 Summary ODD: Overview Design concepts and Details

The basic idea underlying the model is to represent a network of agricultural stakeholders composed of farms and a cooperative (latter called a network of stakeholders) within a mixed landscape in order to test its performances facing hazards. The overall *purpose* of our model is to describe how interactions through biomass exchanges occur within mixed landscapes and to quantify their contribution to resilience at the farm and at the landscape level. Specifically, we are addressing the following questions: *to which extent do specific stakeholder networks improve resilience at both individual (i.e., farm) and landscape levels?* and *what part of their functioning is important for these systems in terms of resilience (e.g. specific network structure, decision rules, etc.)?* We want to test the theoretical hypothesis that *the more interactions between farms, the more resilient the system is.*

To consider our model realistic enough for its purpose, we use the following *patterns*: i) **biomass flows** reflect the intensity of interactions in the stakeholder network and then are used to compute performance and resilience indicators, ii) **network connections** reflect the number and intensity of connections between interacting farms and from which can be computed network indicators. The model includes the following *entities*: farm, cooperative, livestock herd, plot, stock and landscape (farming area and roads) (Figure 8). *The state variables* characterizing these entities are listed in Table 9. A time step in the model represents one year and simulations are run for 18 years. The 8 first years are used to build and initialize the network ("warmup"). Spatial resolution is an aggregation of contiguous farming areas (homogeneous area regarding farming production) connected by roads. In this study, we study Ariège, a NUTS3 region (Nomenclature of Territorial Units of Statistics) composed of 3 farming areas, for a total area of 4 890 km².

The most important processes of the model, which are repeated every time step, are the farms forecast of their needs for biomass needs; the recover of excreted manure in buildings; their exchange with other farms; fertilisation, growth and harvest of crops; grain and fodder exchange with other stakeholders; livestock herd feeding, growth and sell to slaughter activity; and finally farms adjust their trade threshold (Figure 9). This order of execution (livestock production, then crop management, and finally livestock feed) is arbitrary. However, as it represents farm activities within a year and that this forms a cycle (manure from livestock is used to fertilise crops, which are then used to feed livestock), we assume that it does not impact the simulations. Moreover, we assume that farms have a complete knowledge of their needs and therefore forecast accurately at the beginning of the year the amount of biomass needed and used on the farm. Most processes are specific to an individual farm and thus do not directly impact other farms (e.g. crop fertilisation, livestock feeding). Exchange/trade are the only processes that involve direct and indirect interactions through biomass flows between agents during the process. These flows happen between stakeholders and can imply trade-off for resources during

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the interaction phase of the simulation. In order to avoid bias arising from execution order of these processes, farms take actions in a randomized order.

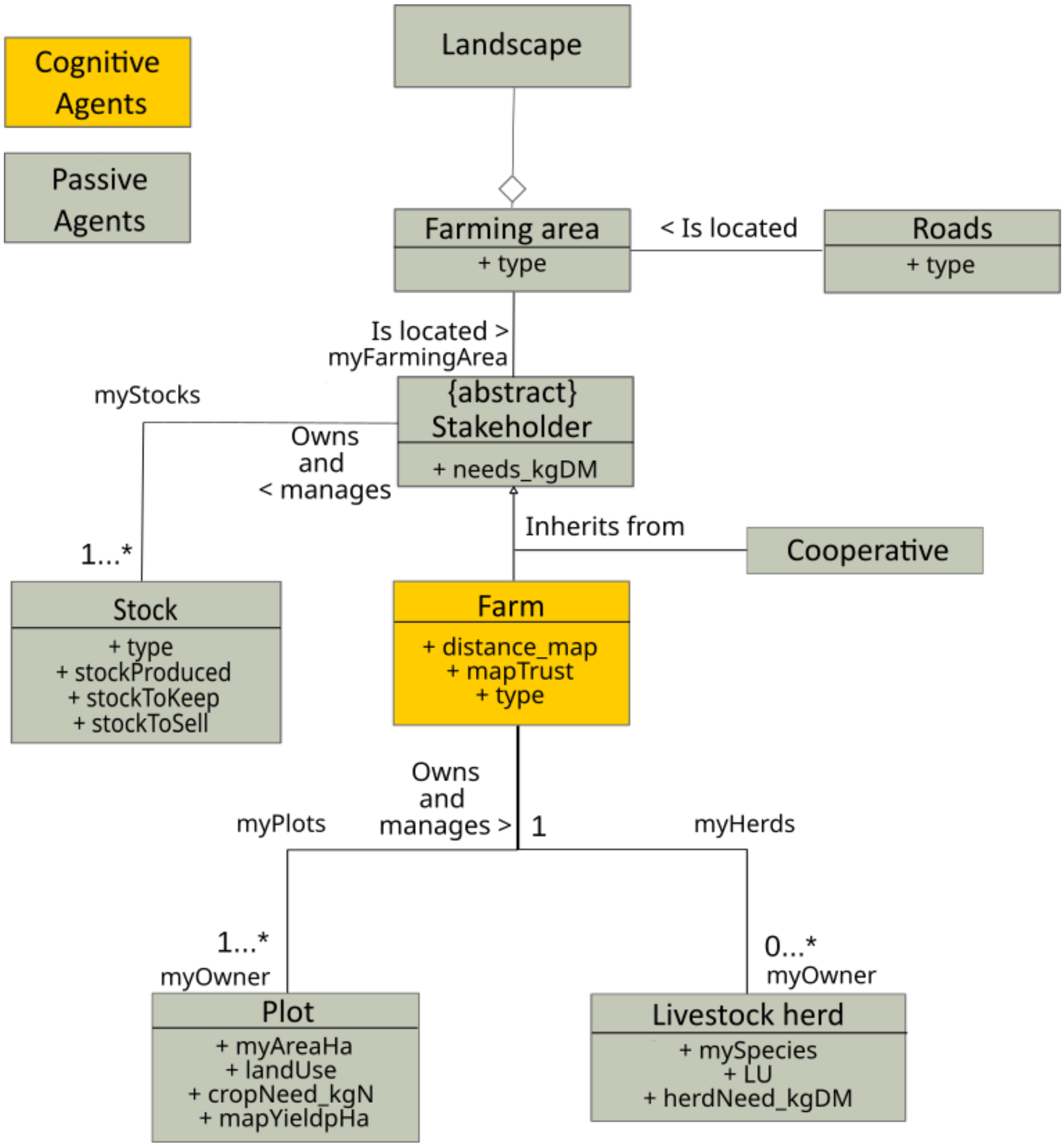

Figure 8: Class diagram: entities of the model with relations among them and attributes.

A class diagram is part of the Unified Modeling Language (UML). It represents the agents of the model (boxes) and their parameters. The farm agent is the only deciding agent, i.e. cognitive agent. The others are driven by internal processes or by the actions of the farms, i.e. passive agents. The diagram also represents ‘associations’ between agents (solid line). These associations are binaries, they can be specified and directed. For instance, farm agents own and manage plot and livestock herd agents. Multiplicities of associations are given as an interval (minimum…maximum). An asterisk * expresses that there is no restriction. For instance, one farm agent can own and manage one or more plot agent, when one plot can only be owned and managed by one farm agent.

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Table 9. Entities and state variables model (on the 3 following pages)

Agent	Name	Description	Type	Unit	Range/Values	Changes	Usage
Farming Area	type	Type depending on agro-pedo-climatic conditions	string	dml	Set of ‘farming area types’	static	Init
	myRoads	Road belonging to the landscape	list<road>	dml	Set of road	static	init
Road	type	Road type	string	dml	Set of ‘road types’	static	init
Plot	myAreaHa	Area of the plot	float	ha	>0	static	sim
	myOwner	Owner and manager of the plot	farm	dml	Set of farm	static	sim
	cropNeed_kgNpha	Manure fertilisation dose needed for the plot	float	kgN/ha	0-*	time step	sim
	landUse	Land use of the plot	string	dml	Set of land uses	static	sim
	mapYieldpHa	Yield reached for each biomass type of the plot	map<string = biomass, float = yield>	kgDM /ha	<Set of ‘biomass, see biomass yield>	time step	sim
	mapPlotProduction_kgDM	Production of live vegetation biomass	map<string = biomass, float = quantity>	kgDM	0-*	time step	sim
Stakeholder (farm and cooperative)	myFarmingArea	farming area belongship of the stakeholder	landscape	dml	Set of Landscape	static	Init
	myStocks	Stock managed by the stakeholder	list<stock>	dml	Set of stock	static	sim
	needs_kgDM	Needed product quantity by biomass type	map<string = biomass, float = need>	kgDM	<Set of biomass, 0-*>	time step	sim
Farm	location	Point where the head office is located	integer	dml	Set of values within the farming area	static	init
	ID	Farm unique identifier	string	dml	Set of farm	static	sim
	type	Typology for agricultural holdings	string	dml	Set of farm ‘type’	static	sim
	myPlots	Plots owned and managed by the farm	list<plot>	dml	Set of plot	static	sim

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Agent	**Name**	**Description**	**Type**	**Unit**	**Range/Values**	**Changes**	**Usage**
	myHerds	Livestock herds managed by the farm	list<livestockHerd>	dml	None or set of livestockHerd	static	sim
Farm	mapStoringRate	List of biomass storing rates in farm for each product	map<string = product, float = storing rate>	dml	<Set of product, 0-*>	static	init
	network	List of farm in the farm's network	list<farm>	dml	<Set of farms>	static	Sim
	reputationScore	Farm reputation in its network	float	dml	0-1	time step	Sim
	mapTrust	List of other farms and trust attribute for each	map<farm, integer = trust value>	dml	<Set of farm, 0-1>	time step	Sim
	mapTrustEvolution	List of modifications of trust in other farms	map<string = farms ID, map<integer = trust value, float = cycle>	dml	<Set of farm, <0-1, 0-*>>	time step	Sim
	mapRelationOverBiomassShare	Farmer preference for relational over biomass criteria in trades for each biomass category	map<string = biomass category, float = farmer orientation>	dml	<Set of biomass categories, 0-1>	static	sim
	infoAcceptance	Weight of farm acceptance to incoming information	float	dml	0-1	static	Sim
	networkInfluence	Network weight for farm rate threshold computation	float	dml	0-1	static	sim
	mapTradeIteration	Number of times the farm remained in the trading loop	map<string = biomass category, float = number of iteration >	dml	<Set of biomass, 1-*>	time step	VERIFICATION
	farmRateThreshold	Threshold above which potential traders are kept in the partner selection process	map<string = biomass category, float = farm rate threshold>	dml	<Set of biomass, 0-1>	time step	Sim
	mapSatisfactionTrades	Store farm satisfaction by biomass	map<string = biomass category, boolean = farm satisfied>	dml	<Set of biomass, [TRUE;FALSE]>	time step	Sim

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Agent	Name	Description	Type	Unit	Range/Values	Changes	Usage
	nbCompletedTrades	Number of completed trades with each other farm	map<farm, float = number of completed trades>	dml	<Set of farm, 0-*>	time step	Sim
	nbBrokenTrades	Number of broken trades with each other farm	map<farm, float = number of broken trades>	dml	<Set of farm, 0-*>	time step	Sim
Farm	coveredNeedFarmToFarm	Part of buyer's need that have been covered by trades with other farms for a given biomass	map<string = biomass, float = need covered rate>	dml	<Set of biomass, 0-1>	time step	sim
	coveredSellingFarmToFarm	Part of seller's need that have been covered through trades with other farms for a given biomass	map<string = biomass, float = need covered rate>	dml	<Set of biomass, 0-1>	time step	sim
Livestock Herd	mySpecies	Species of the herd	string	dml	Species	static	Sim
	LU	Number of animals in the herd	float	livestock unit (LU)	0-*	static	Sim
	stockingRate	Livestock stocking rate	float	LU/ha	0-*	static	init
	herdNeed_kgDM_pLUpday	Biomass required each day by LU	map<string = biomass, float = herd need>	kgDM/LU/day	0-*	static	sim
	nbDaysBuilding	Days spent in building in a year	float	days	0-*	static	sim
	nbDaysEstive	Days spent in estive in a year	float	days	0-*	static	sim
	mapHerdProduction_kgDM_pLUpday	Biomass produced each day by LU	dml	kgDM/LU/day	<Set of biomass, 0-*>	static	sim
Stock	type	Type of biomass	string	dml	biomass type	static	Sim
	mapStockToKeep	Stored biomass quantity that is kept on farm depending on its origin	float	kgDM	<Set of biomass origin, 0-*>	time step	Sim

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Agent	Name	Description	Type	Unit	Range/Values	Changes	Usage
	mapStockToSell	Stored biomass quantity that will be sold depending on its origin	float	kgDM	<Set of biomass origin, 0-*>	time step	Sim

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The most important *design concepts* of the model is the individual decision-making of the farms to interact with each other. We framed it according to the MoHub framework (Schlüter et al., 2017). This framework takes into account the data that are perceived by the decision-maker, the rules and process used to select a behaviour and the result, *i.e.,* the behaviour (in our case the choice of an interaction with a specific farm, the cooperative or external market). We adapted the Theory of Planned Behaviour (TPB) and Belief Desire Intention (Rao and Georgeff, 2001) which initially takes into account as rules, from the perspective of the decision-maker: its perception of the social network, attitude (values and beliefs), subjective norm (what he/she thinks is socially accepted or not) and perceived behavioural control (what he/she can really do). In our case, each farm perceives the landscape resource availability to adapt its exchange strategy (e.g. be more demanding for a biomass that is abundantly present in the territory). Each farm also perceives the overall reputation of other farms, which is based on the mean trust of all farms that previously tried to interact with it. This reputation score is used as a basis of trust the first time two unknown farms encounters for trade; the trust in each other is substituted by the reputation score for this first trade attempt.

We consider a network of farms already involved in interactions. To simulate this network we assumed that farms had a positive attitude towards what they would call local interactions and would, if possible first try to exchange/trade locally before exchanging outside of the landscape. Working on the attitude from the TPB, attitudes of one farm regarding another is mainly based on the notion of trust between them, whereas the attitude towards the cooperative is only based on the farm preference to trade with it instead of trading with another farm. Trust here is an aggregate of behavioural beliefs on the functioning of interactions that include prevalence of farm relationships, long-term partnerships, i.e. farms believe that a long-term partner will not fail them, even if there are perceived opportunities and incentives for it (Nooteboom, 2002). A subjective norm would be that the longer the relationship, the more farms expect that it sustains and can be repeated in future interactions. Perception of control is approached by the limitations induced by the context of the farm, e.g. high distance with another farm implying too high costs.

Farms adjust their interactions with other stakeholders, depending on their resources (biomass products), the resources owned by the others and the history of their interactions. They tend to reach their specific objectives by following if-then rules that reproduce observed behaviours. Learning is not included as such in the model. However, farms remember their past interactions with others and will prioritize their exchange with someone they exchanged with in the past.

Stochasticity is included at the initialisation of the model. Each land use area and livestock unit is attributed to farm agents according to their type, within a range of possible values. Manure production rate is set to each livestock owners within a given range and a livestock species is randomly set following farming area distribution.

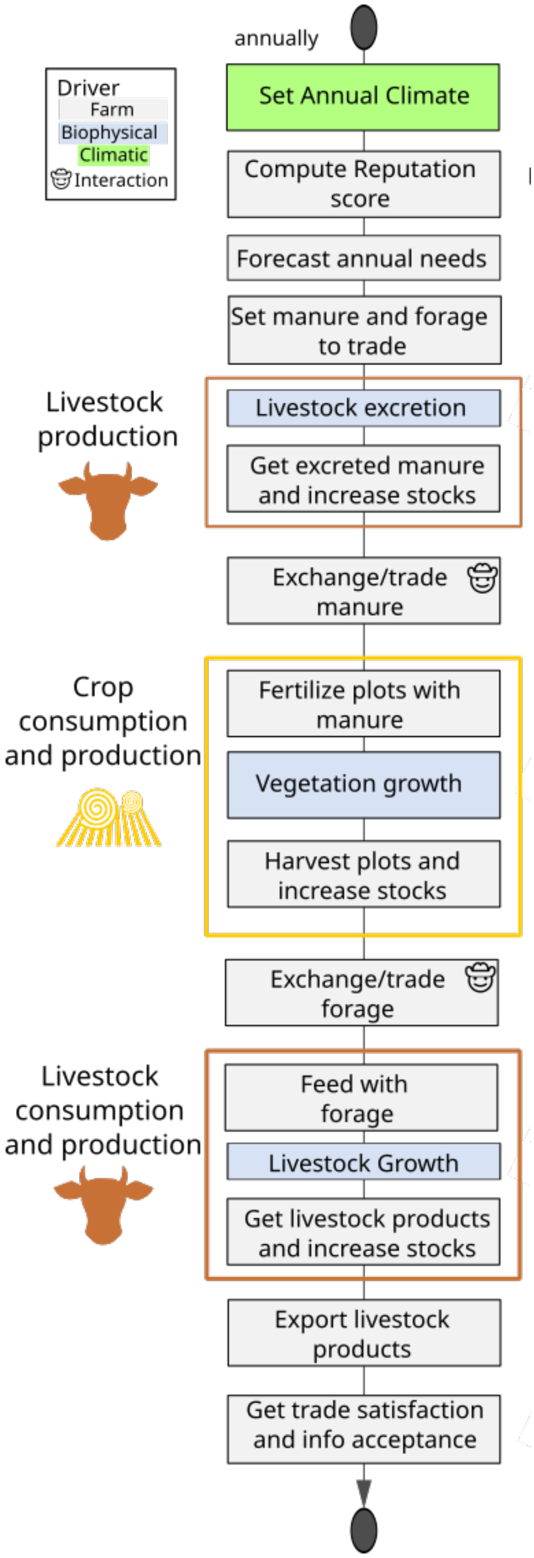

Figure 9: Activity diagram (annual time step).

This diagram shows all activities that sequentially happen within the annual time step of the model.Grey activities are driven by farm agents, blue activities are biophysical processes and green activities are climatic processes. The first brown frame highlights livestock production activities (mean and manure). The next frame (in yellow) highlights crop-related activities, and the last one (brown) highlights livestock feeding activities. All these are the processes considered relevant for our modelling purpose. Interactions are between the farm and other farms or the cooperative.

The model is initialized with an initial null trust value between farms, i.e. they don't know each other at the beginning. First 8 cycles are aimed to create a valued network of trust between farms before any scenario application. Model dynamics are driven by *input data* representing farm structures and preferences toward farm trades (versus cooperative) and geographical distance with neighbours. These data are set thanks to model explorations (see §5.3). They drive farm interactions and how much the cooperative is solicited in the stakeholder network. Stochasticity is included at the initialisation of the model. Each land use area and livestock unit is attributed to farm agents according to their type, within a range of possible values. Manure production rate is set to each livestock owners within a given range and a livestock species is randomly set following farming area distribution. At each step we observe for each farm its need for each biomass and if it has been satisfied. We also observe the biomass flows that come in and out of the farm, as well as the origin and destination of the flow. Finally, we track trust evolution between farms. These allow the computation of farm level balances and stakeholder networks. The model was implemented on Gama (http://gama-platform.org/), a multi-agent simulation and spatially explicit modelling platform (Taillandier et al., 2019).

5.1.2 Focus on decision-making mechanisms for interactions

5.1.2.1 General process to select an interaction partner

When a farm needs a biomass, it may: get it from another farm, from the cooperative, or the global market. As mentioned previously, we built our decision-making process such as farms will first look for a local transaction, with a random chance to be taken out of the logic loop before its end and go to the global market even if some products are still available locally.

We chose a matching problems algorithm which aims to find a match between two kinds of populations. In our case, some farms may need a biomass (demanders), whilst other farms or the cooperative may have extra stock of it (providers). Looking at the matching algorithm, we first started with a matching by pairs, as in the stable marriage problem (also known as Gale-Shapley algorithm, as described in D3.2). However, as a buyer may buy biomass to many other individual (and the contrary), we rather chose an algorithm closer to "college admission" problems where students are matched with colleges. The algorithm takes into account the fact that a college can take multiple students, and also the fact that colleges have limited places. We adapted the French version of the college admission problem ("Parcoursup"). In our case, demanders apply for an interaction for the biomass they need to their top-ranked providers (see ranking in §5.1.2.2), who in turn check on their top list and decide if they will accept the interaction (see Figure 10). If a demander still requires biomass after the interaction, he can ask another provider (creating a loop as long as there is offer and demand). The resolution of the problem might depend on whom starts asking to whom (buyers or salespersons). We set it such as the buyers always start asking.

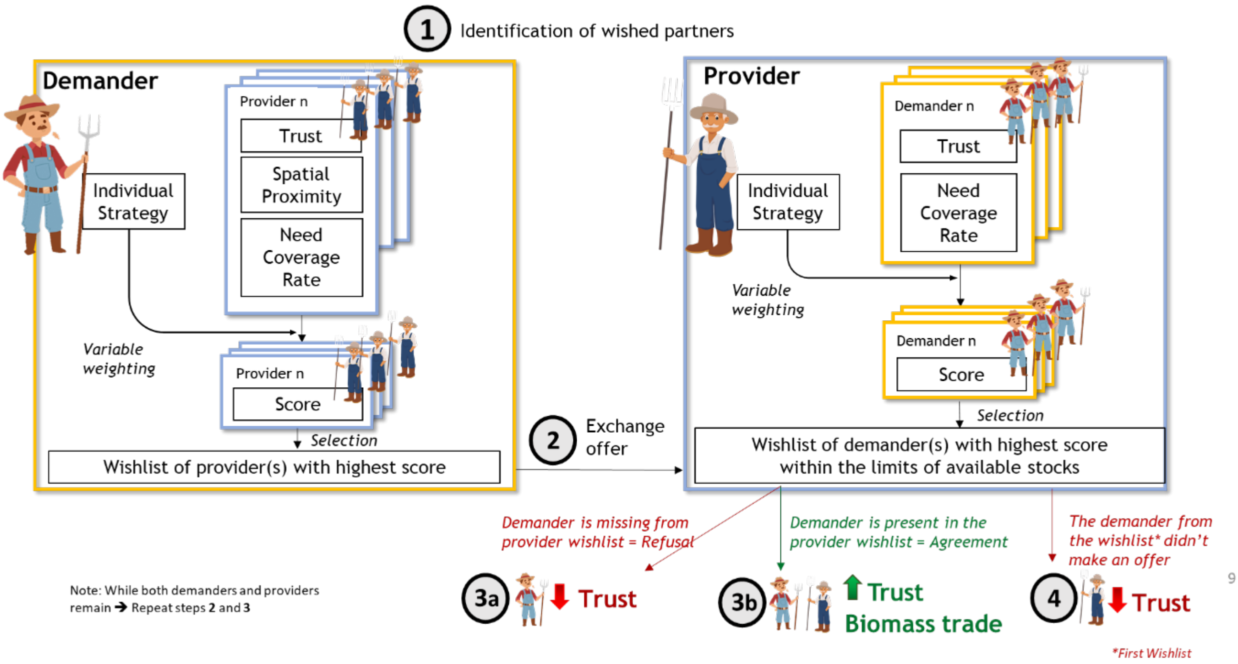

Figure 10: Flowchart of the rule-based decisions for a trade with another farm and the resulting trust evolutions. Sequence follows an ascendant order with two different possible outcome at step 3.

5.1.2.2 Scoring of the other stakeholders

The top ranking list is established through the computation of a score for a given biomass. Each stakeholder who may need or provide the biomass will rate the others. This rating is dependent on their distance (*Proximity_Rate*), their trust (*Trust*) and the need coverage (*Coverage*). The score value may then be different between two partners. It is computed as described in Eq. (1 to rate stakeholder *i* at cycle *t* for the biomass *b*:

$$Trade\_Probability_{i,t,b} = \frac{a_b \times Proximity\_Rate_i + s_p \times Trust_{i,t} + (1 - s_p) \times Coverage_{i,t,b}}{a_b + 1} \quad \text{Eq. (1)}$$

The a_b coefficient [0 to 1] represents the weight of the distance between farms for the decision-making. It is specific per type of biomass (e.g. farmers are less willing to travel long distances to get manure than the other types of biomass so its a_b is higher) and common to all farms. As shown in §4.3, demanders often handle the logistics. Thus, we assume that the buyer is the only one caring for the distance aspect in the rating. Thus for providers, $a_p = 0$. The s_p coefficient is the farm orientation ranging from only relational-oriented trades (1) to only biomass coverage-oriented (0). It depends on the farm.

The three variables *Proximity_Rate*, *Trust* and *Coverage* have been bounded to the range [0,1] to simplify the equation. *Proximity_Rate* is, for a pair of farms, the revert ratio between their distance *i* and the maximal farm-to-farm distance in the simulation. *Trust* is a value between the partners from the point of view of the one who computes it. It evolves through the cycles. We adapted a mechanism from Nooteboom (2003) and Klos and Nooteboom (2001).

If an interaction occur, we consider that farms tend to know each other, reducing future transaction costs. After the second interaction, trust between the two partners may increase. We drew the equation such as the increase rate is diminishing with increasing trades (decreasing to scale), leading to a stable low increase rate in the end. This is what we can observe in real conditions: a trusted partner we already interacted a lot with won't gain much more trust as time goes by. After a trade, cognitive rapprochement between partners occurs. It means that the more they interact the closer are their mindset, their way of thinking and their perception from each other. On the contrary, if a farm expected an interaction with another farm but this interaction does not occur (the other farm chose a better deal, Figure 10 Step 3a or 4), trust, on the side of the deceived partner, will decrease. We added a hazard variable in order to represent unplanned and non-modelled trust parameters (quality of the product, product recovery delays, etc.).

Coverage is the need coverage that farm could get thanks to the interaction with the other farmer *i*. Computation of this variable differs between a demander (Eq (2) and a provider (Eq (3). *Coverage* cannot exceed the need/stock.

$$Coverage\_Demander_{i,t,p} = \min\left[\frac{traded_{quantity}{}_{i,t,p}}{need_{t,p}}; 1\right] \quad \text{Eq (2)}$$

$$Coverage\_Provider_{i,t,p} = \min\left[\frac{traded_{quantity}{}_{i,t,p}}{stock_{to_{sell}}{}_{t,p}}; 1\right] \quad \text{Eq (3)}$$

Farm interactions with a cooperative is handled the same way as between two farms, except that there is no distance limitation ($a_p = 0$; this covers for a simplification for transaction costs), nor trust aspect (*Trust* = 0). The cooperative buy or sell the total quantity desired by the farm (*Coverage* = 1), as a consequence the general Eq. (1) can be resumed into the following Eq (4).

$$Trade\_Probability_{i,t,p} = \left(1 - s_p\right) \quad \text{Eq (4)}$$

Thus, the cooperative will never interact with an only relational-oriented farm (s_p = 1) and most often with an only biomass-oriented farm (s_p = 0).

The length of the list for the top-ranking is defined by a threshold,$farmRateThreshold$. It also depends on the farm and biomass type. With this threshold, a given farm j will only keep a potential partner i that verifies this condition:

$$Trade\_Probability_{i,t,p} \geq farmRateThreshold_{j,t,p} \quad \text{Eq (5)}$$

Each demander has a chance (*aleaTradeWithOutsider*) to trade with a provider that does not belong to his top-ranked providers. Indeed, in reality, two farms may interact due to a specific opportunity (random encounter, a common friend asking for help, etc.). This random phenomena is rendered through this hazard value and let the buyer successfully trade once with a random seller not initially spotted. It is also possible that farms will not trade all of their biomass with others because of this threshold. All remaining needs are then covered by the external market and extra stocks sold to it too.

$farmRateThreshold_{j,t,p}$ is a dynamic variable that can be changed at the beginning of the cycle when the farm has not been satisfied by the previous trading process. This gives the farm the possibility to adjust its level of requirement (or tolerance), depending on its success or failures to trade (Brenner, 2006). It implies that if a demander has been too strict on his provider selection, it will lower its criterion, or threshold, to reach more providers the next time and have more trade chances. Farms could theoretically modify their threshold each year but this leads to wide inconsistencies into farm systems that seems unlikely to happen in real cases. We consider that the farm will trade when it has a reason to, i.e. when it is dissatisfied from its trades. We assume that dissatisfaction happens when it couldn't trade anything or if it performed worse than last time it tried to exchange the concerned biomass.

We want to take into account both farm self-results and landscape resource availability to allow a better farm adjustment to the current situation. Tesfatsion and Judd (2006) present an equation to model one's inspiration level evolution with individual and social influences. We compute for the unsatisfied farm j new threshold value of product p at year t.

$$farmRateThreshold_{j,t+1,p} = (1-\lambda) \times farmRateThreshold_{i,t,p} + \lambda \times [\,(1-z) \times tradeRate_{j,t,p} + z \times networkRateThreshold_{t,p} \quad \text{Eq (6)}$$

With λ, the rate of acceptance of new information, z, the influence of social norms on farm decisions, $tradeRate_{j,t,p} = \sum_i Coverage_{i,t,p}$, the total covered need through trades, and $networkRateThreshold_{t,p}$ the landscape resource availability level. This latter is computed directly from the landscape total amount of biomass produced $quantitySupply_{t,p}$ and its landscape total need $quantityDemand_{t,p}$. Here we consider that the farm has general knowledge on the scarcity of the resource. We should consider demander and a provider NRT:

For demanders:

$$networkRateThresholdBuyer_{t,p} = \frac{quantitySupply_{t,p}}{quantityDemand_{t,p}} \quad \text{Eq (7)}$$

For providers:

$$networkRateThresholdSeller_{t,p} = \frac{quantityDemand_{t,p}}{quantitySupply_{t,p}} \quad \text{Eq (8)}$$

$networkRateThreshold_{t,p}$ is bounded to the interval [0 ; 1] and updated when a strong change in resource availability occurs, i.e. the ratio $\frac{quantitySupply_{t,p}}{quantityDemand_{t,p}}$ (and $\frac{quantityDemand_{t,p}}{quantitySupply_{t,p}}$) shifts from one of these categories to another: {[0 ; 0.25[, [0.25 ; 2[, [2 ; +∞[}.

During the "warmup" cycles (first 8 years) of the simulation, we gradually stabilise the $farmRateThreshold_{j,t+1,p}$ by linearly decreasing the value of λ (the rate of acceptance of new information) toward 0. The reason is that we want to reach simulation stabilisation, and while farm thresholds keep changing this is unlikely to happen as it maintains a high level of competition between traders in case of scarce products. After the 8th cycle, the rate of acceptance of each farm is reset to its initial value but the value of $farmRateThreshold_{j,t+1,p}$ is updated only if the farm is both unsatisfied and territorial resource availability shift occurred.

5.2 Indicators studied

5.2.1 System delimitation

Three levels of organization are studied with the observations of the model: farm, farm network and landscape systems. We particularly focus on biomass flows that circulate within the systems (internal flows) and that comes in/goes out of it (external flows). We consider 6 biomass types: organic fertilizer (manure), inorganic fertilizer (imported), livestock products (meat or milk), crop products (grains), fodder and straw. The biomass flows (kilograms of dry matter, i.e. kgDM) are converted into nitrogen units (kgN) to be comparable.

Farm system is delimited by the farm agent including its plot and herd agents (Figure 11, A.). We study internal biomass flows within the farm and between compartments related to production activities of plots (distinguishing land uses of crops and grasslands) and livestock. Biomass flows coming in or going out of the farm system are external flows. They are flows with other stakeholders (other farm or cooperation), with the global market.

The **farm network system** includes all farm agents (Figure 11, B.). Internal flows are the biomass flows between farms when they exchange. External flows are the flows occurring between stakeholders and the global market or the cooperative.

The **landscape system** includes all stakeholder agents (farms and the cooperative) (Figure 11, C.). Biomass flows occurring within this delimitation are called internal flows, flows coming inside or going outside of the system are called external flows. These latter are exchanges with the market and include biomass surplus not kept in the landscape system and biomass needs that could not be met by exchanges between stakeholders.

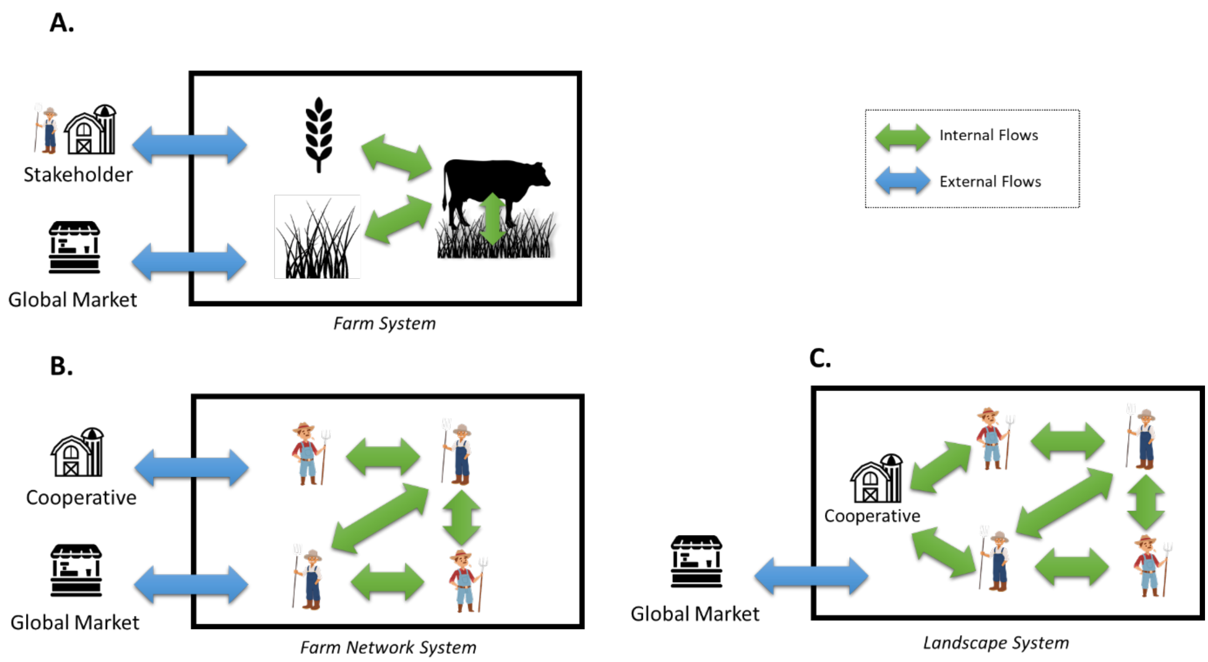

Figure 11: Systems studied with their biomass flows.

A. Farm system. B. Farm network system. C. Landscape system.

5.2.2 Performance indicators

Performance indicators gather nitrogen self-sufficiency, circulation, efficiency and productivity variables. To compute them we defined intermediary variables (Table 10).

Table 10 : List of intermediary quantitative variables. All levels = farm, farm network, landscape

Variable	Level	Unit	Definition
INT	All	kgN	Sum of internal flows
IN	All	kgN	Sum of inflows
OUT	All	kgN	Sum of outflows
TT	All	kgN	Sum of all flows, internal and external (INT, IN and OUT)
Loss	All	kgN	Biomass quantity that could not have been used or exported from the system (e.g. urine, grass)
BNTotal	All	kgN	Annual total biomass quantity needed by the system
BAutoconsumed	All	kgN	Annual biomass quantity consumed by the system
BCBTrade	Farm	kgN	Annual biomass quantity consumed by farm trades
OUT_Plot	Farm	kgN	Sum of plot products
OUT_Herd	Farm	kgN	Sum of herd products

We focus on one farm performance indicator: **self-sufficiency (SS)**. It represents the system independency towards external inputs, i.e. system capacity to produce products and use it for its own consumption to fulfil a given need. Therefore it is computed as the sum of biomass flowing (in kg N) between system compartments divided by the overall system needs (in kg N). This variable is used to compare farm performances in similar studies (Perrin et al., 2020; Stark et al., 2016). We distinguish farm (F-SS), farm with trades with other farms (LS), farm network (FN-SS) and landscape (L-SS) self-sufficiency.

Then we consider one farm network and landscape performance indicator: **internal circulation rate (farm network: FNICR, landscape LICR)** to represent the system independency toward external inputs, i.e. imports from the cooperative and the global market for FNICR and imports from global market for LICR. It is calculated as the sum of biomass flows inside the system divided by the total system through flows (Stark et al., 2016).

5.2.3 Network analysis

We selected network indicators in order to characterize network structure, i.e. the presence of regular patterns in network relations (Faust and Wasserman, 1994). We study a complete network, defined as a network in which we know all nodes and all potential and current connections between nodes. The different network nodes are made up of the stakeholders from the farm network system. This network evolves over time with interactions occurring between nodes.

We consider two different networks according to the nodes and links involved:

- Biomass network, the nodes are the stakeholders and the links are the quantity of biomass traded at the current cycle. We build a biomass network for each biomass category (e.g. grain network, fertilizer network)
- Trust network, the nodes are the farms (no trust aspect with the cooperative) and the links are the mean trust between two nodes (no link if null).

For each of these networks we calculate the following network indicators:

- **Mean trust** is the average of the farm mean trust from the farm network system (trust network only). The farm mean trust is, for a farm, the mean of the trust value with every other farms of its network (i.e. trust value is not null). Farm mean trust reveals whether the farm is investing into few long-term partnerships or into multiple short-term ones, whereas the mean trust of the farm network is an indicator to know the average strength of each of its links.
- **Actor degree centrality (ADC)** is the level of connection of one node with the others. It is calculated as the ratio of its number of connections over the maximum possible number of connections (Faust and Wasserman, 1994).
- **Betweenness centrality (BC)** is the measure of individual position in the network, it shows how much the node is central, i.e. according to Faust and Wasserman (1994), which ones are "in the middle" and can act as "bridges" on other nodes geodesics (shortest path between two nodes). Nodes with a high betweenness centrality have a high potential for control of information flow (Faust and Wasserman, 1994; Freeman, 1978). BC is computed as the number of times a node lies on the shortest path between other node pairs and divided by the maximal potential value, to be less dependent on the network size (Faust and Wasserman, 1994; Freeman, 1978).
- **Betweenness centralization**, or group betweenness centralization, is the generalisation of BC at the network level. It allows the comparison of different networks taking into account the variability of BC of their nodes. For instance betweenness centralization is maximal (1) in a star network with only one central actor connecting all other, and is minimal (0) in a network where all nodes are connected together. It is computed as the sum of difference between each node BC and the maximum realised node BC in the network, divided by the maximum possible value of this sum (Faust and Wasserman, 1994; Freeman, 1978).
- **Density** is the equivalent of ADC but at the landscape level. It is the ratio of present connections to the maximum possible in the network (non directional), or in other words, the average proportion of edges incident with nodes in the graph (Faust and Wasserman, 1994). It shows the level of interaction inside the network (Pachoud et al., 2020). When the density is null no connection is present, when the density is equal to one the maximal number of connections is reached (betweenness centralization is null).
- **Connectivity** is the average path length in the network. This is another indicator to know how dense or compact is the network, it is a measure of its cohesiveness or robustness (Faust and Wasserman, 1994). The lower it is, the closer are the nodes (shorter geodesics). It is computed as the mean of all nodes geodesics.

Network indicators are all bounded between 0 and 1, except for the mean trust and connectivity.

5.3 Model explorations: process and results

In the previous sections we presented how we conceptualized and implemented our agent-based model. In the following section we focus on model exploration. Explorations are an important part of the modelling process, allowing model evaluation and validation of simulation observations (Cottineau et al., 2015). Our process helped us to fine-tune the data workflow of the model: from initialization up to selection of indicators, passing by simulation parameters (Figure 12). We structured our modelling exploration after the following questions:

1. Should we initialise a network at the simulation start?
2. How many agents and how many cycles are necessary to run the simulation?
3. Which indicators are relevant to analyse the model?
4. Which mechanisms with no specific impact on the observations can we remove for model parsimony?
5. How much is the model sensitive to input parameters?
6. Is it necessary to generate different farm location sets?
7. How many times a simulation must be replicated?
8. Which network configuration can be designed from the model?

In the following section, we first describe the different exploration methods we used, and second present the main objectives behind each question and main decisions after exploration. Lastly we present the set of parameter chosen for further simulations.

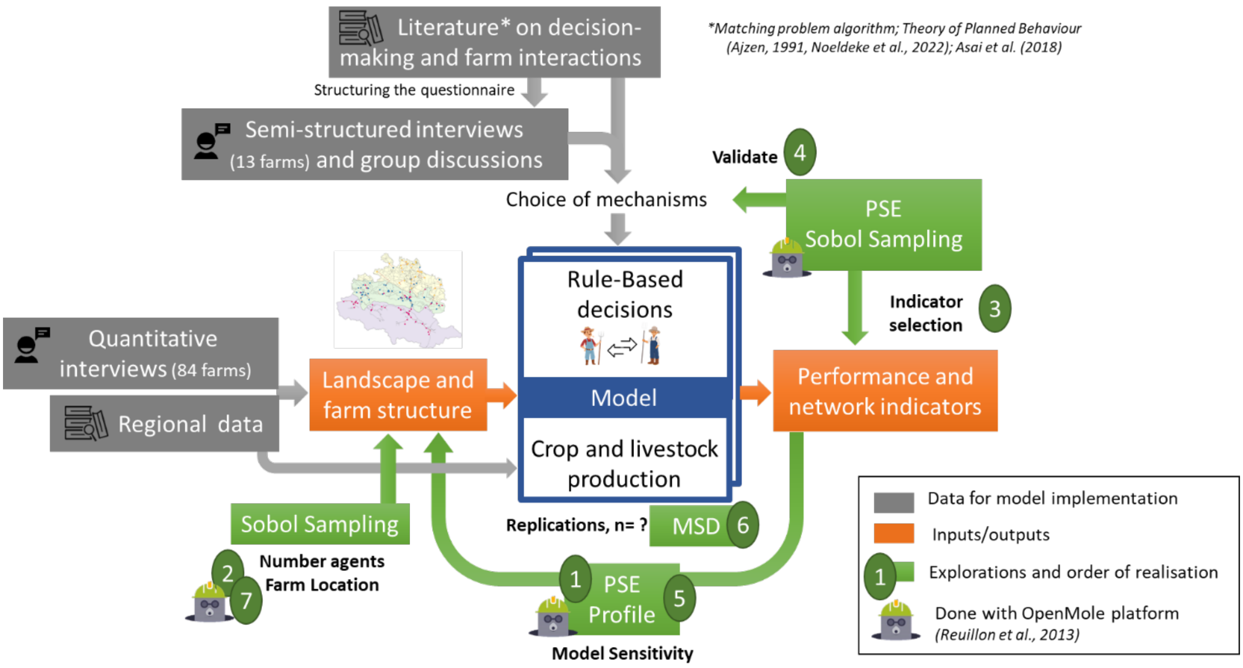

Figure 12. Workflow for model implementation and explorations.

MSD = mean standard deviation. PSE = pattern space exploration

5.3.1 Methods used for explorations

5.3.1.1 Sobol Sampling

We aimed to know to which extent an observed model behaviour can be generalised to all potential simulations with different input parameters. Sobol sampling can serve this purpose. It is a sampling of the input space from a sequence of low discrepancy sequence, *i.e.*, a quasirandom sequence in which the proportion of points in the sequence that falls within an arbitrary set B is nearly proportional to the measure of B, similar to what would occur on average in the case of an equidistributed sequence. It ensures a quicker and broader even coverage of input space sampling than a random sampling (uniformly distributed random numbers).

5.3.1.2 Pattern Space Exploration (PSE)

Pattern Space Exploration (PSE) is a method for exploring the diversity of a model by continually expanding the size of output space patterns. The algorithm samples the values of the input parameters to maximise the diversity of patterns discovered in the output space. As a genetic algorithm, the PSE method considers individuals as simulations whose genome is defined by their input parameter settings. It generates new individuals by combining the values inherited from the parent incorporating mutations (variations in the values of certain parameters). The parents are individuals used for the new generation and selected on the basis of a rarity score. This score is calculated based on the number of times a cell in the region of the output space (grid) is reached. If occurrence is low, the outputs obtained are rarer and therefore the corresponding individuals are more likely to produce new individuals with behaviours that have not yet been observed (Chérel et al., 2015).

The PSE is an open-ended genetic algorithms and because of its heuristic nature, it doesn't have intrinsic end. Thus, the PSE requires launching simulation repeated until it reaches a given number of simulations, used as a stopping criterion. The number of jobs (simulations) varied depending on the exploration needs (desired accuracy of the exploration) and result convergence. An evolutionary algorithm is considered as converged when the new found solutions do not differ from previous ones, i.e. the amount of found solutions reach a stable number (Schmitt et al., 2015). We ran an approximate average of 100 000 jobs by PSE, one model execution being of 8 minutes on average (1min/cycle).

5.3.1.3 Profile

A calibration profile helps modellers to better understand the effects of a parameter on the model behaviour while remaining independent from other parameter variations. The calibration profile technique we used has been published in the paper of Reuillon et al. (2015). As described by Reuillon et al. and Cottineau et al. (2015), for each value of the explored parameter, all other parameters are fitted by a genetic algorithm calibration to minimize a given objective value. Then we can display a graph showing the impact of the explored parameter on the corresponding objective value. The shape of the graph reveals, for instance, if the model is able to produce the acceptable dynamics only in a restricted parameter range, or if the model can be calibrated whatever the value of this parameter because it is compensated by other parameter variations (Cottineau et al., 2015).

5.3.1.4 Implementation of the methods with Open Mole

Like other ABM, our model is highly computation expensive and simulation size is too large to be launched for explorations from local computers. We used the European Grid Infrastructure (EGI) to distribute the workload of our simulations, thanks to the OpenMole platform (Open Model Exploration, www.openmole.org) (Reuillon et al., 2013) that helps modellers to use this technology. The platform uses the technique of the "island model", which is widely described by (Schmitt et al., 2015). Moreover, OpenMole provides a large panel of model exploration methods, including the ones we chose for our modelling questions.

5.3.2 Results of the explorations: decisions regarding model parameterization and mechanisms

5.3.2.1 Should we initialise a network at the simulation start?

Objective: Determine if the network must be set from the start or if it must be built during the first simulation cycles. The answer was not straightforward as there are pros and cons on both sides. Setting a network at the simulation start means that we have to describe how farms are connected in the farm network, i.e. who is connected to whom and how well (trust value). Whereas not defining a network means we need to let the simulation run a given number of cycles, a "warm-up'" phase, to allow network building.

Method: PSE

Main decisions: For trust initialization, each farm agent starts in the simulation without previous knowledge of other agents, i.e. with a null trust for any other one. We chose to have a 'warm-up' phase for a few cycles in order to construct a history of past exchanges before the application of scenarios.

5.3.2.2 How many agents and how many cycles are necessary to run?

Objective: Determine number of agents and cycles (length of the 'warm-up' phase) to get a stabilisation of the indicators. We aim to simulate a whole region that can host thousand farms (2265 farms in 2020 in Ariège, (DRAAF Occitanie, 2022)). However, the more we simulate agents, the more we consume time machine. The number of simulated agents had to be large enough to generate emerging patterns resulting from interactions between agents but minimized in order to limit the time machine consumption. Another issue was that we run non-terminating simulations (Law, 2013), i.e. without natural event in the model that would end the simulation. Thus, we needed to specify the simulation run length corresponding to a stabilisation of observations.

Method: Sobol Sampling

Main Results: We consider our simulation to have reached a stable state after 8 cycles, i.e. length of the ‘warm-up’. We simulate 300 farms to represent the network of farms of the region (Figure 13).

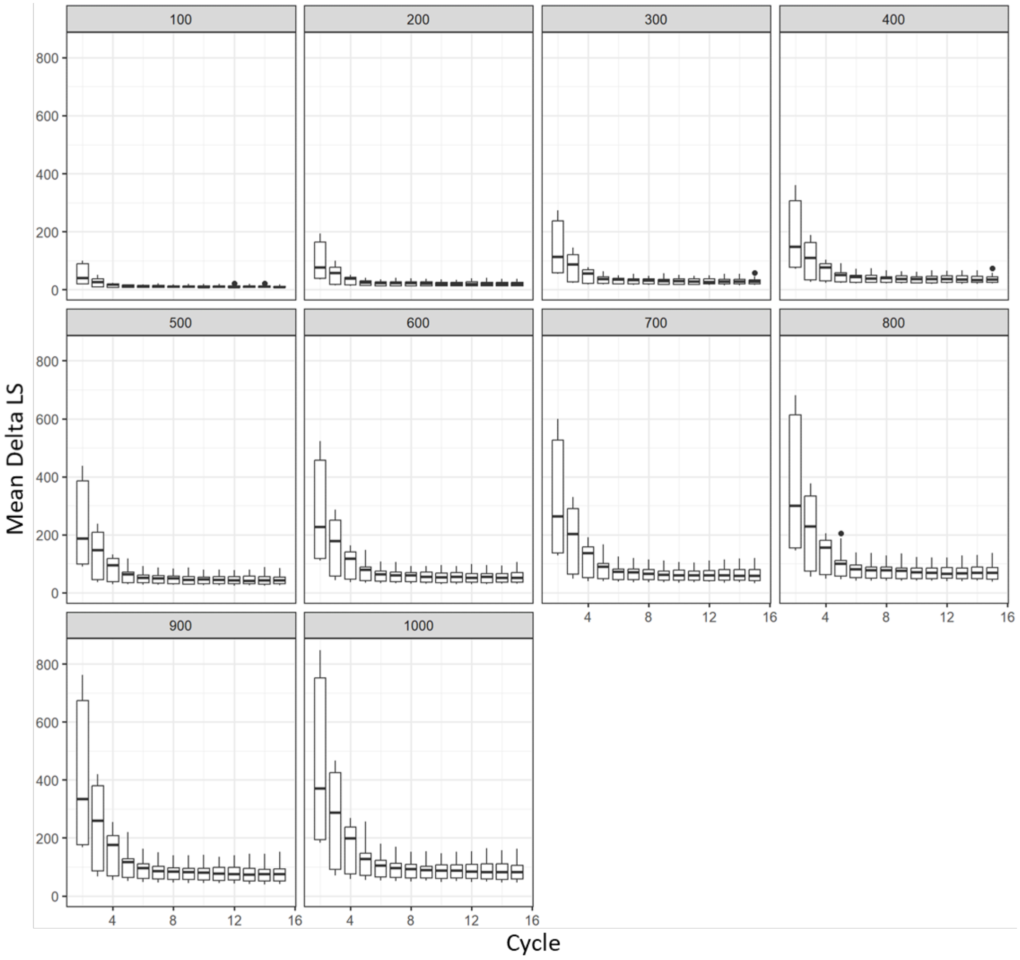

Figure 13. Evolution of the mean delta L-SS (landscape self-sufficiency) by cycle and for 20 repetitions. Each box corresponds to the number of farms initialised in the simulation (100 to 1000 farms).

5.3.2.3 Which indicators are relevant to analyse the model?

Objective: Determine indicators than can return different model patterns in order to evaluate the model. We consider the indicators’ relevance with their capacity to draw a wide range of patterns in the output space, i.e. the ability to return a variety of indicator values depending on the input parameter variations.

Method: PSE

Main decisions: As density does not change over the simulations, it is discarded as an indicator to discriminate explorations.

Complementary observations on the model behaviour: We conducted another exploration to know which autonomy patterns (LS) can result from the simulations, as it is a key indicator in the model. We observed a very low autonomy of crop farms (around 0). It is consistent with reality and implemented mechanisms as their autonomy is only for fertilization, relying only on manure imports which is very scarce in the landscape system. Crop-livestock have the highest LS (0.7 – 1.0) whereas the range is wider and more intermediate for livestock farms (0.25 – 0.75).

5.3.2.4 Which mechanisms with no specific impact on the observations can we remove for model parsimony

Objective: Describe the model sensitivity to specific mechanisms and decide if they must be kept and for which values. We aimed to check whether few detailed mechanisms implemented in the model could help us gain in precision for modelling farm behaviours the model, or create a contrary result due to an increase of uncertainty with an addition of hypothesis on their behaviours. Indeed, as agent-based models are not deterministic and unplanned patterns may emerge, different initial conditions even inadequate mechanisms can conduct to the same observed results. The mechanisms could also have no impact on the observations but still increase time computation, which is also not desired.

Method: PSE

Main Results: contract mechanism adds more complexity to conceptualize the mechanism without new behaviours, they are not kept. We also selected the trust equation that only consider the number of broken past trades (“Completed_Trades”), the most straightforward equation. Finally we keep the threshold mechanism as it allows farms more adaptability for farm interactions with the following parameter values:
- initInfoAcceptance influences in the same time and oppositely LS and modularity. We choose a value of 0.3 as a trade-off between a decrease of modularity and increase of LS.
- initFarmRateTheshold shows most stable patterns around 0.6. However, it corresponds to low value of LS. In order to maximize LS we consider a lower value, such as 0.4.
- initNetworkInfluence can greatly influence modularity and LS, with a breaking point around 0.5. We should consider to keep this value in order to obtain a stable pattern diversity.

5.3.2.5 How sensitive is the model response to input parameter variations?

Objective: Describe the model sensitivity to input parameters. Model sensitivity is an important and unavoidable step of modelling. At this stage, we must understand specifically to which input parameter the model responds most, in which case and how. For instance, to which extent can the model be calibrated to reach given objective values (indicators) when one of the input parameter is set to a specific value while the other parameters are set free? This helps us to set the input parameters to remain in the simulation’s “acceptable dynamics”, i.e. the parameter settings that enable to stay close to the observed objective value.

Method: Profile & PSE

Main Results: The initBiomassOverRelationShare coefficient is significantly and positively correlated with LS for livestock farms, as long as the score threshold doesn't evolve.

5.3.2.6 Is it necessary to generate different farm location sets?

Objective: Describe the influence of the initial location of farms on model outcomes. Farm agents are located in a given area in the simulation and their interactions depend in part on the distance separating them. It is reasonable to assume that the initial farm location influences the trade distances.

Method: Sobol Sampling

Main decision: We use the same map for all simulations, i.e. farms of the different farm types have a fix location from one simulation to another, but not a fixed structure (e.g. total area, area per land use, etc.).

5.3.2.7 How many times a simulation must be replicated?

Objective: Determine the number of replications simulations. Contrary to deterministic models, where the simulation outputs will always be the same with the same input parameters and data, stochastic model simulations can return a range of different values, even if they start with exactly the same initialisation. To take into account the variability of our simulations, and consequently output indicator variability, we must replicate the simulation several times as we cannot rely on a single simulation. This means that we must define the optimal number of times the simulation has to be launched in order to capture the model output variability, while keeping this number as low as possible for machine time consumption reason.

Method: Mean standard deviation

Main Decision: 15 simulation repetitions is sufficient

5.3.2.8 Set of parameters after exploration

Explorations helped define a set of input parameters for further simulations according to their influence in the model (Table 11).

Table 11: Parameters explored with their description, range and value set after the exploration.

Category	**Variable**	Description	Range	**Value after exploration**
Simulation	initNbFarmers	Initial Number of farm agents in simulation	N+	300
	initNbCycles	Number of cycles to run a simulation	N+	8 ('warm-up') + 10 (scenario)
Trust	initTrustBase	Initial trust value for other farms	[0 , 1]	0
	trustOffset	Rate to which the trust increases/decreases after an interaction attempt	[0 , 1]	0,3
	aleaSatisfactionRange	Range to which the trust evolution can be altered (positively and negatively) due to unexpected events	[0 , 1]	0,5 (range of [-0.5 , 0.5]
	cognitiveRapprochementRate	Rate to which both partner trust values get close to each other after a trade	[0 , 1]	0,2
	trust_equation	Trust increase equation (used after each trade)	3 choices	Completed_Trades
getRate Equation	initCoefDistanceSpatial	Initial farm distance spatial weight	[0 , 1]	[0 , 1]
	initRelationOverBiomassShare	Initial farm preference weight between relational and material aspect of the trade	[0 , 1]	[0 , 1]
Trades	aleaTradeWithOutsider	Rate to which a farm is susceptible to trade with an unexpected farm (i.e. not in its desired partners list)	[0 , 1]	0,2
Thresholds	initNetworkInfluence	Initial network influence weight on farm score threshold computation	[0 , 1]	[0 , 1]
	initFarmRateThreshold	Initial farm rate threshold value	[0 , 1]	[0 , 1]
	initFarmInfoAcceptance	Initial farm acceptance towards new information (for score threshold computation)	[0 , 1]	[0 , 1]

5.4 Simulating and comparing two different farm networks

In this section we test whether a ”strong” network, optimized on the trust between farm results in better self-sufficiency performances and different network structure than another where trust is minimized. The underlying hypothesis is that trust is a key lever to improve farm, farm network and landscape performances. We also aim to show the importance of the position of the cooperative in farm strategies. The strength of a network is described by network indicators (e.g. density, betweenness centralisation). We first present the method with simulation parameters then the results and a conclusion on our hypothesis.

5.4.1 Methods for simulation exploring

5.4.1.1 Minimising and maximising mean trust within the network

We explored simulations where the NSGA2 algorithm tried parameter sets (Table 12) in order to either minimise or maximise the *meanTrustNode* indicator for each farm type (average of farms mean trust). We focused on three network indicators in order to analyse diverse network configurations regarding: density, connectivity and betweenness centralisation (Table 13). We then performed statistical tests to compare the resulting network configurations. In order to work on contrasted networks, we assumed that scenarios differed if the median difference was above 30%.

We simulated 300 farmers during 8 cycles for each simulation. Explorations of parameters for minimization and maximisation yielded 100000 simulations each. We kept only solutions that contained at least 100 samples (*i.e.*, that the solution was found at least 100 times) because they are more robust regarding model stochasticity.

Table 12. Input parameters used for exploration in order to get contrasted network configurations

Input Parameter	Definition	Range	Expected outcome if value = 1	Why
initRelationOverBiomassShare	Farm share between trust and biomass aspects of a trade	[0;1]	High density	Farms are more willing to trade with other farms instead of cooperative when close to 1
initCoefDistanceSpatial	Farm importance attached to trading distance	[0;1]	Low density Low connectivity	Geographically distant farms have less chance to interact when close to 1
initFarmRateThreshold	Initial rate threshold value	[0;1]	Low density Low connectivity High centralisation	Trades are less susceptible to occur when close to 1
initInfoAcceptance	Initial info acceptance for rate evolution	[0;1]	Unstable network over time	Threshold values evolve greater when this parameter is close to 1
initNetworkInfluence	Initial network influence on rate	[0;1]	Unstable network over time	Network influence is higher when close to 1, while farms' own situation is less important

Table 13. Network indicators used to define contrasted network configurations

Network Indicator	Definition	Range	Why
Density	Ratio of actual number of edges divided by the potential number of edges	[0;1]	Show degree of interconnection between farms
Connectivity	Mean distance between farms	[0;1]	Show relational distance between farms
Betweenness Centralisation	Variance of centrality between farms	[0;1]	Reveal differences of centrality between farms

We used the R software to perform the statistical analysis. We compared scenarios based on their indicator mean (or median) values with a significance threshold of 0.05 for the p-value. When comparing more than two modalities (difference between farm types by scenario), we performed an ANOVA and tested the same assumptions.

5.4.1.2 Parameter sets for minimization and maximisation of trust

Explorations yielded 10 different solutions for the Min modality and 19 different solutions for the Max modality. These set confirm that we cannot have a single parameter setting that would satisfy all of the three objectives but that there is rather a balance between them.

We selected for the Min modality the parameter setting that would minimize most of the three normalized errors on objectives but with parameter values that would be logical in case of the minimisation of mean trust node by farm, e.g. low initRelationOverBiomassShare. We didn't consider the parameters with a null value for the threshold parameters (e.g. initInfoAcceptance) as we aimed to use this mechanism. For the Max modality we kept the parameter setting with a high initRelationOverBiomassShare (higher preference for farm trades), a high initCoefDistanceSpatial (farms are more concerned by trade geographical constraints) and a low initFarmRateThreshold (less restrictive selection of potential partners), to increase farm interactions, and low normalized errors (i.e. closer to maximal observed indicator values). Selected parameters are shown in Table 14.

Table 14 : Selected Parameter Settings for Min and Max modalities

Parameters	Min	Max
initRelationOverBiomassShare	0,23	0.76
initCoefDistanceSpatial	0,56	0.83
initFarmRateThreshold	0,05	0.02
initInfoAcceptance	0,05	0.54
initNetworkInfluence	0,83	0.17

5.4.2 Comparing two different networks

Between cycle 1 and 8, we observed a decrease in the number of traders with the cooperative from 271 to 215 in the Max300 while it remained stable around 253 traders in Min300. It means that in Max300, farms are progressively turning towards the farm network rather than keeping trading grain with the cooperative. At cycle 8, we observed a lower mean number of partners within the farm network in Min300 than in Max300 (1.4 and 1.1 respectively for cereal grain).

Similarly as for the number of partners, during 8 cycles for Max300 we observed an increase over time of the quantity traded within the farm network while decreasing with cooperative trades (+200 tN in farm network and -270 tN in cooperative trades). In Min300 there was also an increase of quantity traded between farms over time (+89 tN) and a decrease for trades with the cooperative (-13 tN). Total quantity traded either with other farms or with the cooperative were significantly different between both scenarios, with higher quantity traded in farm network in Max300 than in Min300 and the opposite for cooperative trades.

We also observed significant differences for autonomy indicators LS, FN-SS and FNICR with higher in Max300 (+27%, +7% and +26% respectively compared to Min300 median values). Most of the difference can be explained by a significant difference on grain trades (+27%, +24% and +69% respectively compared to Min300 median values) (Figure 14). LS is directly bound to the amount of biomass the farm is able to get from other farms when needed whereas FN-SS and FNICR are correlated to the quantity traded between farms. As in Max300 the incentive for a higher preference for farm trades pushed farms to allow higher quantity to trade in the farm network, LS, FN-SS and FNICR values increased. In addition, only grain is traded with the cooperative and it explains that when the preference is higher for farm to farm trades it involves mostly changes in grain trades as less grain is traded with the cooperative.

These observations were contrasted depending on the farm type considered. Indeed, livestock grain LS median was 71% higher in Max300 than in Min300 whereas it was only 5% higher with crop-livestock LS. Indeed, livestock farms are the main grain demanders in the network as they do not produce grain at all, contrary to crop-livestock farms.

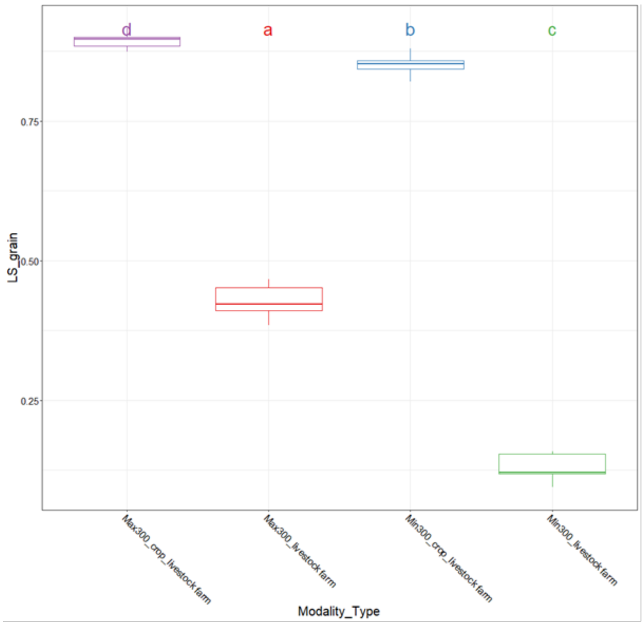

Figure 14: Tukey post-hoc test applied to Welch ANOVA for the grain LS with modalities grouped by scenario and farm type.

Significance threshold is 0.05. Letters above the boxplots (each associated to a given colour) corresponds to a group identified with the test. Crop farm type is not represented as it has no need for grain.

Considering network indicators, we found that values for Max300 were significantly higher than in Min300 for the connectivity (+19%), connectivity for the three farm types (+13% livestock, +14% crop-livestock, +21% crop), BC for grain overall (+62%) and by farm type (+54% livestock, +65% crop-livestock, +84% crop farms). Connectivity and BC results showed that the median distance between farms increases and that the median farm centrality increases too, especially for crop farms. It suggested that in a farm network with higher number of partners and biomass flows this adds more intermediate farms in the network, increasing connectivity, and that some farms embeds more connections than other. We confirmed this result with a significantly higher betweenness centralisation in Max300 for the grain network (+6%) than in Min300.

We also noticed that the density was higher in the Max300's farm network (+23%). Farm trades were closely related to trust indicators, as the BC in the trust network was significantly higher in Max300 (+ 4%) and especially for the crop BC (+ 44%) (Figure 15). Contrary to grain network, trust network had a significant lowest density in Max300 (-2%). ADC and meanTrustNode were not overall significantly different between scenarios. We observed significant differences for farm types: higher livestock ADC (+16%), lower crop and crop-livestock ADC values (-8% and -25% respectively) in Max300 compared to Min300. We also observed significant differences by farm type for trust indicators (meanTrustNode): lower for livestock (-7%) and higher for crop (+11%) in Max300 compared to Min300 (Figure 16). This emphasizes the higher competition between livestock farms for grain trades: they are more numerous to trade with other farms and even if enough quantity is produced in the landscape ($LSS_{grain} = 1$), there are few potential grain providers, being mostly crop farms (24 in the landscape) as crop-livestock farms first consume their own grain and have few or no surplus. This leads to one-way relationship where crop farms have the choice of their partner but not the livestock farms. This explains why we observed a low crop ADC with higher meanTrustNode in Max300 as they are able to choose their desired partner in a long-term partnership. On the contrary, to crop farms that must rely on several unstable partners to keep access to grain (higher ADC, lower meanTrustNode).

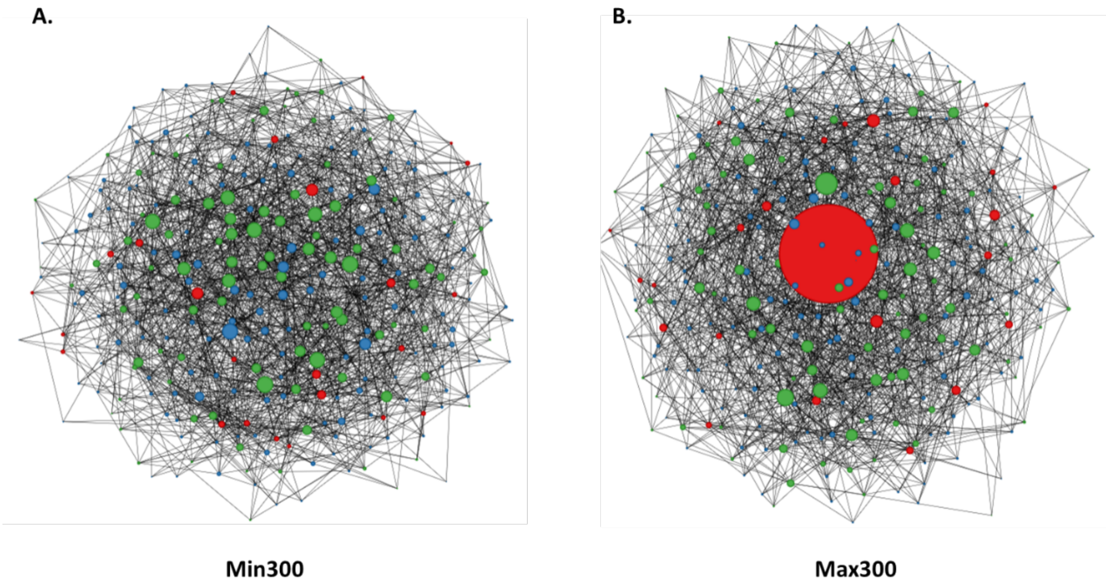

Figure 15: Graph of farm trust networks with scenario Min300 (A) and Max300 (B).

Each dot is a farm coloured regarding its type (crop in red, livestock in blue, crop-livestock in green), sized by its BC value. A line between two farms is represented if their mean trust is higher than zero.

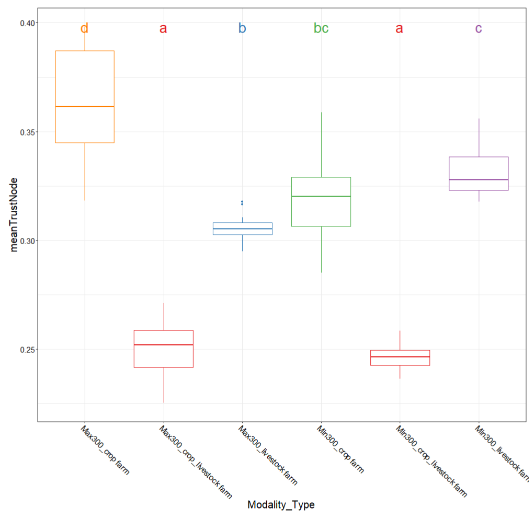

Figure 16: Tukey post-hoc test applied to Welch ANOVA for the meanTrustNode with modalities grouped by scenario and farm type.

Significance threshold is 0.05. Letters above the boxplots (each associated to a colour) correspond to a group identified with the test. A modality with multiple letters belongs each of these groups.

5.4.3 Discussion on the results of the simulations

We developed a model that can simulate a network of farms within a landscape. This model takes into account a set of factors including logistical issues (distance) and social preferences. Simulating individuals allows for a multi-level analysis at farm, farm network and landscape levels. This is necessary to understand how the farm network is structured and the consequences at farm level.

We identified two different parameter settings that lead to contrasted simulations where farms are either more attracted by the cooperative or encouraged to trade with other farms. Farm networks resulting from both scenarios are characterised by a different level of "strength": Min300 farm network is smaller, farms being closer to each other in the network while trading less biomass quantities. On the opposite, Max300 farm network is larger as some farms were attracted from the cooperative toward the farm network and the overall biomass quantity traded is significantly higher. Consequently, farm and farm network performances increased in Max300 while landscape performances remains unchanged. An unexpected result was the higher competition between livestock farms for grain trades leading to a more unequal provider-demander relationship in the favour of crop farms than in the other scenario. Crop farms centralised more biomass flows around them, replacing in some ways the cooperative role in the farm network. Farm network "strength" difference mainly affects specialised farms; crop-livestock farms are less affected by these changes as they can rely on their own production and less on the farm network or the cooperative.

These simulations are useful to reflect on the structure of the networks and situation of a landscape. In this case, for most of the biomasses, the most limiting factor to self-sufficiency is the fact that there is no match between offer and demand. There would need a structural change of the farm, for instance towards more diversification. In a situation, as it is the case with the group of farmers we studied, where farmers redirect their products from the cooperative to other farms, we can alter for a risk of changing the power relations between farms (with central farmers). In another way, we can consider these potential central farmers as key actor to sustain farm interactions. The model can be further used to apply scenarios on contextual changes (e.g., climatic, structural with a decrease in the number of farms).

6 General discussion, perspectives and insights for policymaking

Interactions among farmers (as well as between farmers and other actors) are crucial for the development of mixedness at the landscape level. In this deliverable, we studied them under different points of view: the characterisation of their diversity in the different case study, the analysis of the main reasons encouraging farmers to interact, and the role played by interactions (and their characteristics, such as trust) in the resilience of the landscape. This deliverable starts methodologies that can be surely continued, for example the inventory of farmers interaction and reasons for interact can be extended with other case studies. However, some general considerations can be made in relation to interactions, with some considerations for perspectives and for policy interactions.

Interactions are diverse and fundamental for building mixed landscape. Flow of goods, services, and animals are the main vehicle for the circulation of nutrients within landscapes and for the provision of ecosystem services. This is fundamental in case of specialized but complementary farm, as for example crop and livestock farmers, but it is also important in for farms which are already mixed. In the Romanian case study, for example, interactions among mixed farms are important for helping extending the diversification in all the farms. Interactions among farmers are diverse and take different forms and are the main vehicle for building mixedness at the level of landscape. Therefore, it is important for policymaking to encourage, protect, facilitate interactions among farmers via some forms that will be highlighted in the following points.

Not all interactions lead to mixedness. While interactions are a necessary condition for building mixed landscapes, it is also true that mixedness is not built upon any type of interaction. First, we need to remark that our analysis is mainly qualitative. The quantification is necessary for finding the good balance leading effectively to nutrient recycling. To give examples, sending livestock to other farms or to pastures outside farms is beneficial for animals and for the pasture in principle, however attention must be paid to overgrazing, and to animal welfare in case transportations distance are too long. Second, some interactions are well established, but they do not necessary lead to mixedness. For example, the exchange of products among farmers and the exchange of land to optimize rotations are mostly oriented to building rural vitality, local economy and food production, which might not be necessarily compatible with nutrient recycling in the long term. In any case, the study of all the interaction (e.g., how they are established, how they are regulated) is important in order to find models applicable to the interactions to be promoted.

Logistics and proximity are key factors. Physical proximity and logistic factors significantly influence farmers' decisions to engage interactions, especially for feed-manure exchanges. Exchanges between cereal and ruminant farmers are more likely where distances are manageable and transportation costs are shared equitably. It is therefore important to facilitate infrastructure that make transportation easier. Cooperatives can play a role in reducing distances, some farmers can sell to the cooperatives who further distributes.

Role of social networks and intermediaries. The role of social networks and intermediaries is crucial for mixed systems, where many interactions are based on formal agreements grounded in trust and mutual understanding. Our analysis over the different case studies and the more in-depth analysis in the Ariège case study revealed that a factor encouraging interaction is the need for farming diversification, improve the quality of the production and engage into business partnership. These interactions are often informal relationships evolving into long-term partnerships. The lack of formal structures can sometimes create challenges in terms of scalability and resilience. To address this, policies might encourage the development of social networks and intermediaries through possible measures: 1) reinforcing the role of cooperatives, which operate locally and facilitate connections among farmers; 2) promoting the training and support of advisors specialized in farmer relations; these advisors should adopt a landscape / watershed, rather than farm-specific, perspective and build knowledge that is tailored to the local territorial context. The role of cooperatives is also highlighted by the scenarios simulated with the agent-based model. The model showed that in scenarios where farmers trade directly with other farmers, without the mediation of cooperatives, there is a risk of unequal distribution of benefit among farmers, centralizing the control around few key farms.

Climate change as a main barrier for interaction. Climate change was mentioned as a barrier for interaction. Indeed, climate events can negatively affect production, leading to a decreased quantity of goods to exchange. Policy should focus on climate adaptation strategies for agriculture, such as promoting resilient farming practices. Often, knowledge about these practices are generated by farmers in their specific context. This enforces the need to put farmers into communication and to promote the role of cooperatives, which facilitate the exchange of information in addition of the exchange of goods.

Bureaucracy seen as a main barrier for interactions. In the case studies, bureaucratic constraints and regulatory restrictions were consistently identified as major barriers to fostering interactions between farmers. To address these issues, policies should focus on reforming regulations that limit farmers' ability to participate in local markets, thereby reducing unnecessary administrative hurdles. Additionally, policy could encourage collective action by introducing subsidy schemes based on achieving specific outcomes at the landscape scale, also oriented to climate change adaptation, rewarding collaboration and joint efforts among farmers to enhance productivity and sustainability.

Ensuring equal benefit distribution within the landscape. The modelling exercise revealed that landscape-level benefits do not necessarily translate into equal gains for all farmers. It is therefore essential to ensure that resilience and benefits are achieved at both the landscape and individual farm levels. Simulated scenarios demonstrated that landscape-level resilience can sometimes be achieved even when benefits are concentrated among key farms, leaving others excluded. This highlights the importance of using both landscape-scale and farm-scale indicators to assess outcomes comprehensively. Extending this logic, careful attention must be given when designing subsidies for collective action to ensure that benefits are equitably distributed across the farming community.

Formal *vs* informal contracts. The analysis of various case studies and the more in-depth examination of the Ariège case study revealed that interactions among farmers are often based on long-term collaborations and informal exchanges. These relationships are typically not regulated by contracts, though in some instances, formal contracts are desired. We believe that the need for policy intervention in the formal *vs* informal contracting spectrum is case-specific, and thus, no general recommendations can be made. However, some principles may be applied to varying degrees depending on the context:

1. **Build and promote trust in cooperatives**: Policies should contribute to building trust in cooperatives through quality assurance programs and by financially supporting their governance. Local cooperatives are rooted in the territory and are aware of local farmers' needs. This strengthens local autonomy and can encourage greater farmer participation, leading to the creation of the contract types or informal agreements better suited to farmers' needs.
2. **Promote the use of formal but flexible contracts**: While informal agreements offer flexibility, they can lead to misunderstandings and conflict. On the other hand, formal contracts provide security also for insurances but often lack adaptability. Policies should promote formal contracts that incorporate flexibility for contingencies, allowing for renegotiation in response to significant market changes or unforeseen circumstances.
3. **Recognize and support informal interactions**: Informal interactions are frequently overlooked by policy frameworks. Policymakers could formalize recognition of these exchanges through small grants or incentives that reward cooperation, thereby strengthening local networks and reducing barriers to further integration.
4. **Support long-term partnerships for agroecological transition**: Long-term collaborations between farms often lead to deeper integration and even changes in cropping systems, contributing to agroecological transitions. Policy frameworks should encourage these long-term partnerships by offering incentives for gradual integration, promoting sustainable agricultural practices.

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A. Appendix: correlated submissions

This deliverable was originally dedicated to a pure modelling work, however along the process we thought it was necessary to perform semi-qualitative analyses in order to better explore the interactions among actors in the landscapes. The publications effort therefore went in that direction, with the modelling paper in preparation for submission in the next months.

International conferences:

The following publications underwent peer review and are in the form of short papers submitted and presented at the IFSA conference 2024, in Trapani, Italy.

Accatino F., Triolet C., Dalgaard T., Gavrilescu C.A., Leonte J., Meuwissen M.P.M., Ramos M.C. dos, et al., 2024. Analysing farmer biomass, product, labour and land exchanges in a range of European landscapes, in : IFSA 2024 – European Farming Systems Conference. Trapani, IT. https://hal.inrae.fr/hal-04653765

Grillot M., Meunier C., Triolet C., Ryschawy J., 2024. Crop-livestock interactions between farms: how and why do they occur? A case-study in Southern France, in : IFSA 2024 – European Farming Systems Conference. Trapani, IT. https://hal.inrae.fr/hal-04651135

Conferences in France within communities working on model exploration and mixed farming systems:

Peter A., Grillot M., Gaudou B., Reuillon R., 2024. Simuler des réseaux céréaliers-éleveurs pour évaluer leur capacité d'autonomie locale : Application en Ariège, dans : Colloque du RMT Spicee 2024. Présenté à Les interactions culture-élevage, leviers de résilience des agricultures face aux crises du XXIème siècle ?, Spicee : Structurer et Produire l'Innovation dans les systèmes ayant des Cultures et de l'Elevage Ensemble, Montpellier, France, p. 3p. https://hal.science/hal-04520073

Peter A., Reuillon R., Gaudou B., Grillot M., 2023. Exploration d'un modèle multi-agents qui simule des réseaux céréalierséleveurs : PSE et échantillonnage par suite de Sobol, dans : MEXICO 2023 : Rencontres annuelles 2023 du réseau Mexico. Palaiseau, France. https://hal.science/hal-04547786

B. Appendix: Interview guide

Comprendre les systèmes d'échanges
entre éleveurs et céréalier

Guide d'entretien

Date de l'enquête :

Nom enquêteur : **Durée de l'enquête :**

Exploitation : **Personne enquêtée :**

Rôle dans la ferme :

N° de téléphone : **Mél :**

Personnes présentes :

1. L'exploitation et ses interactions avec le territoire.

Présentation du schéma de flux en format A3. Ex.

1. **Si schéma existant pour une année antérieure, validation du schéma**

Est-ce que le schéma suivant vous semble correct pour l'année …… ?

Est-ce qu'il y aurait des choses manquantes ? (Corrections si besoin)

2. **Actualisation/création du schéma des flux pour l'année 2021.**

Renseigner le schéma pour 2021. éléments à considérer :

- ☐ *Paille*
- ☐ *Fourrages, fauche*
- ☐ *Pâturage*
- ☐ *Fumier*
- ☐ *Destination des récoltes (détaillé si pas 100% à la coopérative)*
- ☐ *Matériel partagé*
- ☐ *Main d'œuvre partagée*
- ☐ *ETA*
- ☐ *Structure de conseil*
- ☐ *Groupe d'agriculteurs*

⚠ *Identifier de manière visible les ajouts ou suppressions en 2021.*

3. *En parallèle, renseigner la carte réseau. Ex.*

Page 1 sur 3

Pour chaque interaction : Paille, Fourrages, Pâturage, Fumier, Récoltes, noter les éléments de réponse suivants :

- Comment vous avez réfléchi à cette interaction ?
  - Comment vous avez choisi l'interlocuteur ? (lien : famille, voisin, même groupe de travail, ami, etc.)
  - Quelles était vos motivations ?

- Depuis quand faites-vous ces interactions ?
  - Comment est-ce qu'elle a commencé ?
  - Qu'est ce qui fait qu'elle continue aujourd'hui ?
  - Qu'est ce qui pourrait y mettre un terme ?

- Quelles sont les modalités de vos interactions ?
  - Fréquence, Quantité
  - Avez-vous un contrat ? Si oui :
    - Quelles sont les modalités du contrat ? (Oral / Ecrit ? Temps de réalisation ? Durée ? Matières échangées ? Quantités ?)
    - Pourquoi faire un contrat ?

Depuis (année .... / ces dernières années), certaines interactions ont-elles été modifiées ? arrêtées ? démarrées ? pourquoi ?

  - Quelle(s) interaction(s) ? Avec qui ?
  - Pour quelles raisons ? Que s'est-il passé ?
  - Qu'est-ce qui vous déciderait à interagir / échanger de nouveaux ?
    - Modalités ?

Plus globalement,
- Quels sont les flux que vous voudriez pérenniser, supprimer, transformer ou créer ?
- Est-ce que vous sauriez dire ce qui vous a freiné / encouragé à faire des interactions ou non ?
- Est-ce que l'orientation de votre système (bio ou conventionnel) à influencé vos interactions ?

Après avoir finalisé le schéma de flux pour 2021, vérifier s'il manque des personnes sur le schéma réseau

Résilience des systèmes

- Est-ce que le schéma des flux de 2021 que l'on a dessiné correspond à une année normale ?

- Quelles seraient les modifications pour une année humide ? pour une année sèche ?

- Est-ce que les prix du marché impactent vos interactions ? Eleveur : *Par exemple, lorsque le prix d'achat des céréales à la coopérative est moins élevé que celui de l'interaction.* / Céréalier : *Par exemple, lorsque le prix de vente des récoltes à la coopérative est plus élevé que celui de l'interaction.*

Règle de décision pour une interaction

On va maintenant s'intéresser à vos facteurs de décisions qui vous font choisir de réaliser ces interactions. Pour cela, on va procéder à une petite activité. Je vais vous présenter plusieurs facteurs types, issus de la littérature et des travaux précédents, et je vais vous demander de les classer en fonction de leurs importances pour vous sur l'échelle entre « C'est très important pour moi », « Ça m'est égal » et « Ça ne m'importe absolument pas ».

✐ Avoir des étiquettes plastifiées et le squelette de la pyramide.

On va réaliser ce classement pour les interactions :

- Fumier contre Paille
- Fourrage ou pâturage
- Aliments / Grain → E : *achat d'une culture spécifique implantée en accord avec un céréalier* / C : *implantation d'une culture spécifique en accord avec un éleveurs*

Facteurs à classer :

1. On a un contrat écrit
2. On a un contrat oral
3. On fixe un prix stable sur plusieurs années
4. C'est le meilleur prix du marché actuel
5. On pourra être flexible et s'arranger sur les dates
6. Ça me permet d'être moins dépendant des coopératives
7. Ça m'apporte un service agronomique (apport de matière organique, destruction de couvert)
8. Je l'aide quand il a besoin, il m'aide quand j'ai besoin
9. C'est donnant-donnant
10. J'ai confiance en mon interlocuteur, il va respecter ses engagements
11. On pourra être flexible et s'arranger sur les quantités
12. L'interlocuteur a des connaissances techniques qui m'assurent une bonne qualité
13. C'est pour rendre service (solidarité)
14. Je peux facilement le joindre
15. On est d'accord sur un calendrier qui sera respecté
16. Le coût logistique est faible
17. La distance à parcourir est faible

Eléments de discussions permettant d'expliciter les choix et la compréhension des cartes. Ex. Distance faible : qu'entendez-vous par faible ici ?

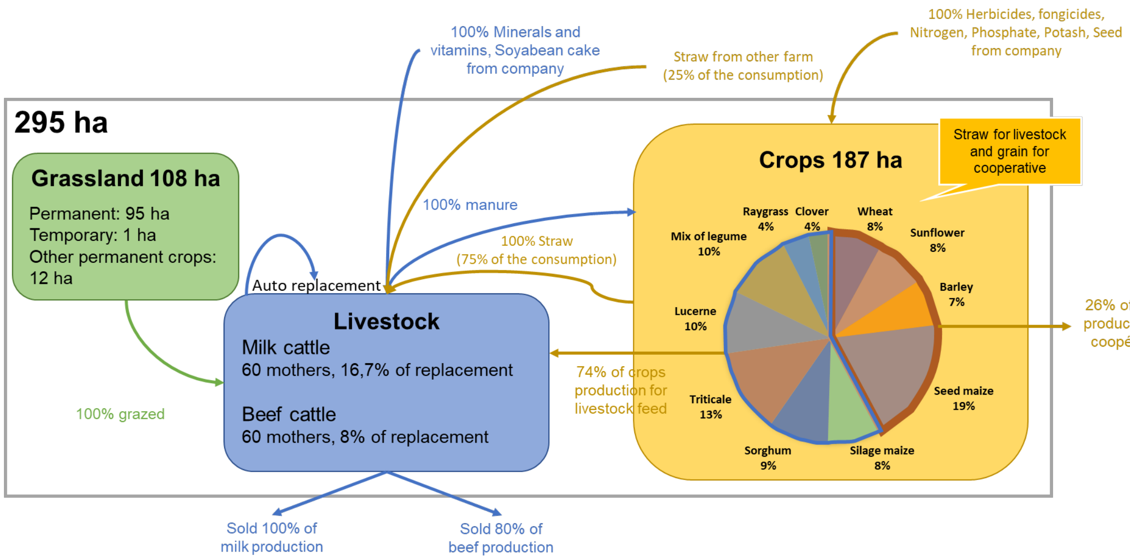
Fin d'entretien

Est-ce qu'il y aurait un sujet que nous n'aurions pas aborder et qui vous semble important à mentionner ?

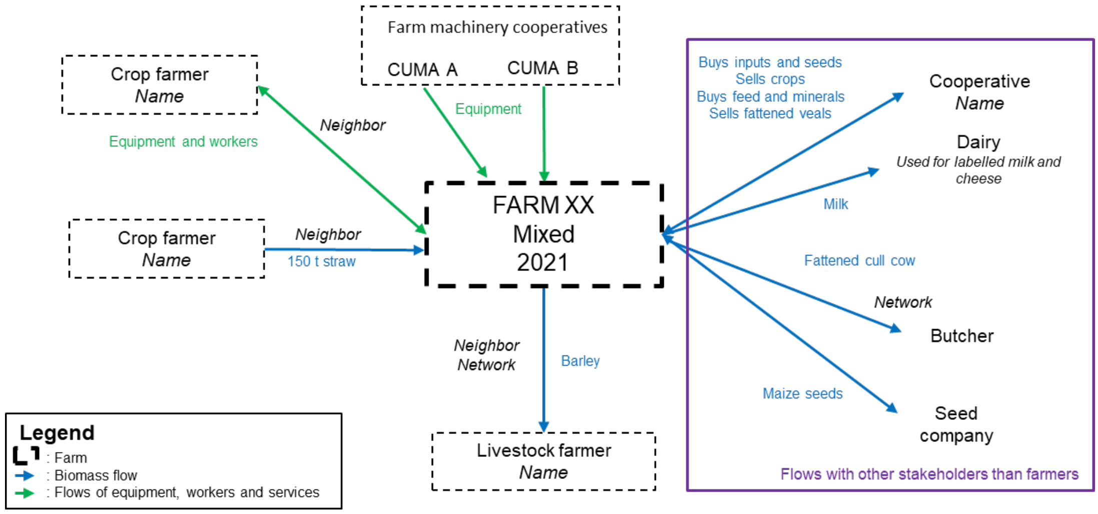
Merci pour votre accueil.

Rappel de la fiche d'information si besoin de nous recontacter.

C. Appendix: example of diagram flows used before, during and after the interviews



Example of diagram flow showed to and build with the farmer during the interview. Focus on biomass flows



Example of diagram flow showed to and build with the farmer during the interview. Focus on social network