MIXED
EFFICIENT AND RESILIENT
MIXED FARMING & AGROFORESTRY

MIXED	
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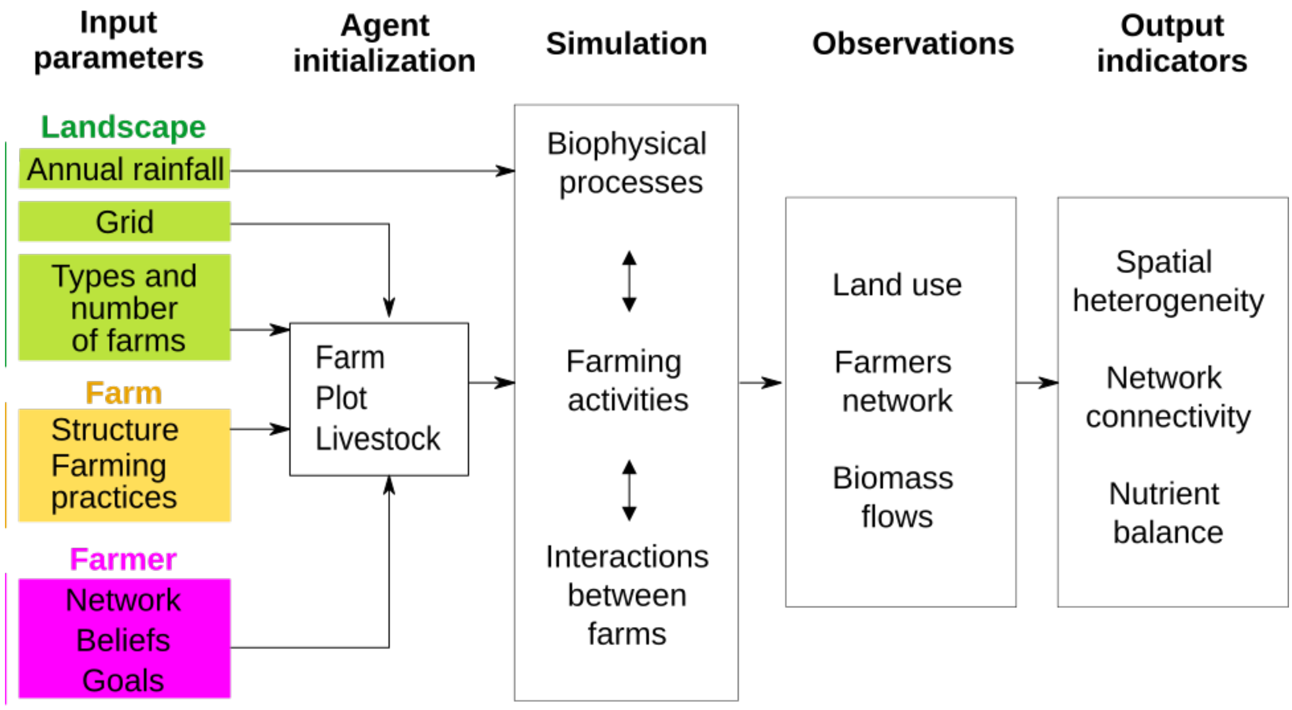
Executive summary

In the MIXED project, we hypothesised that mixed farming and agroforestry systems (MiFAS) have higher resilience and climate adaptation potential than non-mixed systems. It is hypothesised that they have a more integrated coupling of nutrients and carbon cycles, deliver more diversified ecosystems service and a better utilization of resources. The project tackles mixed systems at different levels, including farm, landscape, value chain, country and Europe. This document is a deliverable for task 3.2 where the target level is landscape level.

In order to test the hypothesis of an improved resilience in mixed landscape, we aim, in task 3.2, to characterize mixed landscapes in Europe and assess effects of "mixedness" on resilience to climate change impacts, efficiency (e.g., reduction of environmental impacts) and ecosystem service delivery at the landscape level. More precisely, we aim to provide an in-depth analysis of farm interactions in selected landscape networks.

This deliverable aims to describe how we characterize these farm interactions within mixed landscapes, through an **agent-based model**. The purpose here, is to describe the model. Indeed, a MiFAS at the landscape level can be represented as a set of farms that produce agricultural product and ecosystem services and interact among themselves in a given landscape. In this representation, each farm is conceived as a stand-alone object within a landscape, in an agent-based model. Interactions among farms can be represented by fluxes of manure or feed, or even information.

Model simulations can compute farm network through farm interactions. Individual representation of each farm makes it possible to explore the role of each farm in the landscape (e.g., some farms might be more important than others as they constitute key nodes in the landscape for manure and feed). It will also compute biomass flows that will be used to compute simplified nutrient balances within each farm according to their configurations and the fluxes.



Abbreviations

Abbreviation	Definition
ABM	agent-based model
FM	fresh 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

The importance of promoting the sustainability, efficiency, and resilience of agricultural systems is increasingly recognized at different levels: from the farm, to landscape, to the whole of Europe. In the MIXED project, we hypothesised that **mixed farming and agroforestry systems** (MiFAS) have higher resilience and climate adaptation potential than non-mixed systems. This hypothesis follows some scientific literature that highlights the benefits brought by MiFAS including a more integrated coupling of nutrients and carbon cycles, the delivery of more diversified ecosystems service and a better utilization of resources (Kronberg et Ryschawy, 2019; Martin et al., 2016).

The "mixedness" of agricultural systems is addressed at different levels in the MIXED project. Accatino et al. (2021) provide definitions for the different levels of MiFAS used within the project: *farm*, *landscape*, *value chain*, *country*, and *Europe*. As a common factor for all these levels, the definition of "mixedness" implies two conditions: a **diversity of elements** (activities, actors, functions) and an **integration among them**, having the final aim of promoting circularity and synergies. For example, crops can provide feed to livestock, which, in turn provides manure that decreases the need for synthetic fertilisation (Pinsard et al., 2021).

Work Package 3 (WP3) is devoted to the **landscape level**. This level is one of the most difficult when it comes to setting boundaries. Following Accatino et al. (2021), a landscape can be conceived in two ways. Firstly, it can be considered as a "farming system" consisting of a network of farms and other actors that interact formally or informally within a specific agro-ecological context (Giller, 2013). Secondly, it can be considered as a set of land covers and land uses comprising a certain area; such an area can be defined as the area occupied by a farming system, or as an area delineated by administrative boundaries such as NUTS2 or NUTS3. These two ways of conceiving a landscape lead to different ways of investigating the "mixedness" of a landscape.

In the first case, landscape "mixedness" is created by actors that interact in a given territorial context, for example by exchanging excess feed or manure. In the context of the MIXED project, we call this a *bottom-up* approach, as it starts by considering the interaction among individuals and shows emerging collective patterns at the territorial level. Indeed, the interactions among farms, with exchanges in manure and feed is what can potentially make a landscape "mixed" even though it is composed by specialized farms.

In the second case, landscape "mixedness" is created by the diversity of land covers and land uses, as well as the diversity of farm typologies in a given area. We call this a *top-down* approach, as it starts by considering large scale information and synthesizes it into landscape-level metrics. The tasks of WP3 are distributed in the following way: T3.2 concerns the bottom-up approach, T3.3 concerns the top-down approach, and T3.4 expands upon T3.2 and draws some conclusions and lessons learnt from comparing the bottom-up and top-down approaches.

This deliverable is issued from T3.2 where we aimed to characterize mixed landscapes in Europe and assess effects of "mixedness" on resilience to climate change impacts, efficiency (e.g. reduction of environmental impacts) and ecosystem service delivery at the landscape level. Following Accatino et al. (2021), resilience at the landscape level is given by elements such as the diversity of farm types, feed self-sufficiency at the landscape level and connectivity among actors in the landscape. The influence of these elements on resilience can be tested by means of an agent-based model. Indeed, with an agent-based model it is possible to simulate scenarios; for example, how resilient a system is based on different degrees of connectivity among farmers. The agent-based model was developed in T3.2 with the longer-term purpose of applying it to real farming networks in T3.4. The MIXED project involves networks in different EU countries as case studies, of which 7 are potentially applicable to WP3. Familiarising with the networks and farming dynamics (e.g. agricultural production, farm interactions) is fundamental for making modelling choices and for understanding which of these networks can be studied using the agent-based modelling approach.

The purpose of this deliverable is to provide a preliminary description of the networks involved in WP3 and of the agent-based model formulated for T3.2. The model description is intended as a first version of the model that will be further developed in the next steps of the modelling exercise. An increased knowledge of the networks is important for understanding the basic processes involved and to better fine-tune the model in the next steps.

In this deliverable, we first present why we chose an agent-based model and how the purpose of the model was defined. In this first section, we describe the 7 networks that serve as case studies, according to explanatory interviews with network coordinators, and how we then translate them to a conceptual model. We subsequently describe the model according to the ODD protocol defined by Grimm et al. (2020). The acronym ODD stands for: Overview, Design concepts and Details. As mentioned by Grimm et al. (2020), "Each of these categories serves a different purpose: giving an overview, explaining how design concepts important for ABMs were used, and explaining all the details of the 'machinery' of the model."

2 First steps towards a model

2.1 Why an agent-based model?

Following the *bottom-up* approach, MiFAS at the landscape level can be represented as a set of farms that produce agricultural products and ecosystem services and interact among themselves in a given landscape. **Interactions among farms** can be represented by fluxes of manure or feed, or even information, that are exchanged among farms. Crop-livestock integration at landscape level is typical of such interactions, where crop specialists interact with livestock specialists.

Interactions among farms require coordination. In their review, Martin et al. (2016) showed how various levels of coordination lead to different forms of integration between farms; the more farms coordinate, the more there is integration between farms towards greater synergy. They showed that integration depends on 3 types of coordination between farms: spatial, temporal and organizational. **Spatial** coordination refers to the possibility that farmers might coordinate themselves in order to share a common spatial resource. **Temporal** coordination implies that scheduling might be taken into account in order to coordinate farm interactions. **Organizational** coordination implies that farmers might organize logistics, or perform strategic planning, for instance regarding crop rotations in order to coordinate with other farms.

In addition to the various forms of coordination among farmers at landscape level, Asai et al. (2018) highlighted that other factors are also important in assessing how farmers interact. These included a variety of **operational costs** restricting the implementation of crop-livestock integration of farms. Strong barriers were related to the 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 assume 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 **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.

Agent-based models (ABM) haveen been widely used for studies on farming systems integrating a diversity of farming systems and behaviours (Appel et Balmann, 2019; Catarino et al., 2021; Huber et al., 2018). ABMs are suited for the representation of our *bottom-up* approach, for the following reasons. ABMs can represent different sets of behavioural rules, from complex to random and with more or less coordination among themselves. In our case it is important to test different criteria of choices implemented by the farmers (e.g. how much to exchange, with whom to exchange). ABMs make it possible to represent the heterogeneity of individuals; in our approach it is fundamental to represent diverse farmers (for example crop farmers, livestock farmers, and mixed farmers) with different behavioural criteria, limited perceptions and knowledge of the surrounding environment.

ABMs can take into consideration individuals' interactions with their environment; in our case, it would allow us to take into account the operational costs identified by Asai et al. (2018), but also take into account the social networks in which they evolve.

2.2 Rationale for setting the model purpose

The philosophy here, as suggested by Edmonds et al. (2019), is to build a model with a specific purpose in mind, and not to build a model for the sake of modelling. In order to define the modelling purpose, we needed to know more about the general context of the study, and – more specifically – the farm networks involved. Within the 14 case study networks identified for the MIXED project, 7 networks are selected for analysis in WP3 as they deal with interactions between farms (see Table 1): Hagens Moellebaek (Denmark), Scotland (United Kingdom), Bavaria (Germany), Ariège (France), Ținutul (Romania), Veenkoloniën (The Netherlands), Alentejo (Portugal).

Between January and February 2021, T3.2 leaders consulted with the coordinators (within the MIXED project) of each network involved in WP3. Other colleagues who have a good knowledge of the network were also invited. The aim of these expert consultations was to get a global picture of each network (knowledge of the networks, agricultural context, description of the farms at stake, farm interactions). These 7 expert consultations lasted between 30 min and 2 hours, depending on the data that was already available and published (the more data published, the shorter the interviews).

The information gathered through the consultations were then analysed in order to describe the structure of the networks (see Table 1, e.g. number of farms, farm products, farm interactions) and draw out possible motivations of why the farmers to interact with each other (see Table 2, e.g. how would the farmers benefit from interactions with other farmers). We then performed an in-depth analysis of the information gathered through the consultations and existing material from the networks to start the abstraction of the networks leading towards the conceptual model (see Table 3).

The objective of the analysis of the insights obtained from the consultations was to highlight what had to be taken into account in the model; that is, defining which are the main issues for these networks regarding farm interactions. That involved finding out the following:

- Do we need the model to be spatially explicit? Are farmers facing issues regarding spatial coordination? Do farmers share common spatial resources (e.g. animal grazing on crop farms)?
- What temporal scale is the best fit? Are farmers facing temporal coordination issues that lead to trade-offs regarding some activities? For instance, is there a need for feeds whilst they are not yet harvested? When spatial resources are shared through grazing animals, is there tight schedule between the end of the period when animals are grazing and the next cropping activity has to take place?
- Do we need to model the organisational coordination of the farmers? In other words, are the interactions between farms organized and coordinated by farmers themselves or by another party? Does the model have to include logistics? Do farmers share common resources (e.g. spatial resources, farm equipment, labour)? Is there anticipated strategic planning between crop and livestock farmers in order to balance supply and demand? What is the impact of social networks?
- Reflecting on resilience, what are the main challenges that would most likely impact these networks? Are we going to focus on resilience towards specific events (e.g. climatic, policies, social, market events)?

On-farm interviews will be conducted in 2022 via task T2.3, and these will be used to fine tune our network descriptions and modelling choices.

2.3 Description of the 7 networks

Consultations of the network coordinators ascertained that the current extent of knowledge and descriptions of the 7 networks was heterogeneous. In 4 networks, the area of research and farm productions were well-known. They were described from previous projects for Denmark (Odgaard et Vestergaard, 2014), France (EIP-AGRI, 2018) and the Netherlands (Reidsma et al., 2019, see p193). As for the United Kingdom, the network is coordinated by a farm facilitator and advisor. Trials were set in 2020 with livestock from Western Scotland grazing over the winter in Eastern Scotland but were not yet formally described.

In the networks in Germany, Romania and Portugal, detailed information on the farm activities and interactions practices is not currently available. For Germany, the network is coordinated by an association focused on landscape conservation, some of the farmers are well-known (even though not yet formally described), but not all of them. In Romania, this network presents a new area of research. As for Portugal, the area of research was well-known by the researchers but, no data has been collected in previous projects on agronomic practices, or on farm exchanges.

The global overview (see Table 1) showed that 5 networks have explicit farm interactions at landscape level (Denmark, United Kingdom, Germany, France, The Netherlands). Two networks present mixedness and exchanges at farm level, though no interactions between farms at landscape level (Romania and Portugal). Network sizes tend to be under 50 farms, except for the Netherlands where there will, most likely, have to be a more restrictive selection of interacting farms for the simulations.

Regarding agricultural productions, cereals and cash crops such as potatoes are the most represented arable products. Most animal production relates to cattle, particularly beef cattle. Tree production (fruits, nuts) is under-represented.

Regarding interactions among farms (see Table 2), there is a diversity in the types of objects exchanged, such as live animals (cattle), manure, livestock feed, and land. Interaction objectives also covered a wide range, including for example animal feed self-sufficiency and land conservation. Most farm interactions occur without intermediaries, and when they do, it is through a biogas plant (the Netherlands, Germany). No data is yet available on how farms interact with the biogas plants. However, it seems that in the Netherlands there are various systems: similar to a cooperative with many farmers involved, or two-by-two interactions between farmers.

Table 1: General overview of the 7 networks considered for WP3

Network				Context	Network structure			Production		
n°	Name	Country	Area	Mixed farming characteristics	Level of knowledge by the coordinators (2021-01)	Nb. of farms	Type of exchanges	Arable crops	Ruminants	Non ruminants
2	Hagens Moellebaek	Denmark (DK)	Hagens Moellebaek (2762 ha)	Manure/grass protein exchange within a network of livestock and arable farmers	Farms to be defined, area well known from previous research projects	*11-30	Between farms	Cereals, cash crops (potatoes, vegetable, seed for grass for public areas)	Dairy cattle	Poultry but mostly pig, produce cereals and rape seeds
3	East-West Scotland	United Kingdom (GB)	Scotland (2 trials: Morayshire and Lothians-Ayrshire)	Grazing cattle/fodder exchange within a network of beef suckler herds and arable farmers (East↔West Scotland)	Strong relationship with the farmers, two farm trials currently operating	*1-11	Between farms	Barley (malting-whisky), seed potatoes	Beef cattle (35-40 cows)	-
5	Bavaria	Germany (DE)	In Bavaria (conservation area of 10 000 ha)	(Re)wetting of arable land, exchange of land between arable and livestock farmers	Uneven knowledge of the farmers	*31-50	Between farms	Mostly maize and winter wheat	Beef cattle (self-sufficient) and dairy cattle; number of farms is decreasing	-
10	Ariège	France (FR)	Ariège (NUTS3)	Crops and manure exchange between farms to produce young cattle meat fed on local produced feed sources	Farmers known from previous project	*11-33	Between farms	Cereals, proteaginous crops, mixed crops and cover crops	Beef cattle (40-45 heads of Limousine), sometimes associated to ovine	Farms could include monogastrics work unit associated to cattle (pork/poultry)
11	Ţinutul	Romania (RO)	Near Bucarest (high hills and moutains)	Integrated livestock, natural pastures and trees supporting agro tourism	Farms to be defined, new area of investigation	*31-50	Within farms	-	Dairy cattle (10-15 heads) and sheep (100 heads)	?
12	Veenkoloniën	The Netherlands (NL)	Veenkoloniën (cross NUTS3 regions)	Land and manure exchange within a network of arable (peat, sandy land) and livestock farmers	Farms to be defined, area well known from previous research projects	*>1000	Between farms	Mostly starsh potatoes	Dairy cattle	-
14	Alentejo	Portugal (PT)	Montado of Alentejo region (20 000ha)	Integrated production of pasture, cork and high value meat products based on local pig, cattle and sheep breeds	Farms to be defined, no previous work on farm exchanges	16	Within farms	-	Beef cattle (extensive), also sheep	Pigs

Table 2: Farm interactions in the 7 networks considered for WP3

Case		Exchange	Interest for exchange			Other actors
N°	Name	Matter exchanged within the network	Arable farmers	Ruminants farmers	Non ruminants farmers	Intermediary for exchanges
2	Hagens Moellebaek	Manure, feed, land	Manure	Self sufficiency, too little land to produce roughage	Livestock manure, and in some case feed/fodder	Can be biogas plant (approx. 5 year contract vs less with farmer to farmer)
3	East-West Scotland	Cattle going to crop farm (thus dung/urine and forage)	Manure; loss of fertility and organic matter	The crop farmers produces the forage for winter, cows are in the other area during winter: no more need to keep the cows in barn (expensive: forage and labor cost)	-	None: 2x2 with a contract
5	Bavaria	Change from intensive to extensive greenland landuse	Funding incentives to convert land to grassland on organic soils	Fodder, funding and money incentives to convert land to grassland	-	Biogas plant (corn and wetland fodder)
10	Ariège	Cereals, proteaginous crops, mixed crops and grass (hayed/grazed), manure	Diversifying crop rotations/organic manure	Self-sufficiency for livestock feeding	Self-sufficiency for livestock feeding	2 by 2 exists for now, but cooperatives (large or local with neighbors) could be involved for grain logistics, and for manure a platform is under study
11	Ținutul	Corn	-	Exchange fruits for corn; hay can be produced in the orchards	?	Informal local markets; manure platform (EU legislation)
12	Veenkoloniën	Land	Improve crop rotation	Maybe for forage during drought?	-	-
14	Alentejo	-	-	Self sufficiency (livestock feeding)	None (fed with acorns)	-

Regarding coordination among farms, according to the 3 types of coordination in Martin et al. (2016), the most frequent coordination issues are related to spatial and organizational coordination (see Table 3).

Spatial coordination is essential when land and livestock are the main object of interaction among farms (Denmark, Germany, The Netherlands for land and United Kingdom for livestock) to organize work and to avoid landscape fragmentation. More generally, taking into account the spatial system is important due to operational costs and distance limitations for transport (e.g. farmers will not transport manure more than 25 km as it is financially non viable).

Temporal coordination is least essential for these networks, as most of the time these exchanges can be roughly planned at the beginning of the year. In the case of United Kingdom, as cattle graze on a crop farm, there might be a need for temporal coordination according to the weather conditions, ground holding and sowing of crops.

Organizational coordination is important as intermediaries are not present in all interactions. We find issues of trust between farms (France, The Netherlands), and concerns over logistics (France, Denmark, United Kingdom; e.g. who is in charge of the transportation, and who pays for it and for the possible extra costs). Strategic planning for more integration among farms can also be thought through (with crop rotations in Denmark, United Kingdom, France and the Netherlands).

Portuguese and Dutch network coordinators highlighted high impacts of droughts on their networks. No data is yet available on how farmers adjust their interactions depending on this. Where land exchanges were taking place, network coordinators mentioned public policies as the main drivers and barriers for their networks. Social issues were raised in networks where specialized livestock farmers and specialized crop farmers were interacting. Markets were not considered as major challenge for the networks.

Table 3: Issues encountered in the 7 networks considered for WP3

Case		General issues	Coordination issues		Resilience issues			
n°	Name	Issues to tackle (network)	Spatial coordination	Organizational coordination	Resilience towards drought	Resilience towards land policy	Resilience towards social issues	Resilience towards market
2	Hagens Moellebaek	farm interactions: there is a potential of improvement	can be	yes	-	yes	can be	-
3	East-West Scotland	encourage more farmers to adopt this practice	yes	yes	-	can be	-	-
5	Bavaria	for future: to establish new products based of extensive landuse	yes	-	-	yes	-	can be
10	Ariège	trust establishment and logistics to consider further	can be	yes	can be	can be	yes	can be
11	Ţinutul	?	-	-	?	?	-	?
12	Veenkoloniën	Crop farmers perceive livestock farmers are spreading to much manure on the land	yes	yes	yes	yes	can be	-
14	Alentejo	?	-	-	yes	-	-	can be

2.4 Towards conceptual modelling and first modelling choices

To summarize, the consultations with network coordinators indicated that this ABM should consider:

- diverse farming strategies (e.g. livestock/crop oriented)
- adaptation to production hazard (e.g. lack/excess of products)
- representation of the environment (e.g. spatial distances between farms)
- irrational/unexpected behaviour related to exchanges between farms
- flexibility for applications to diverse mixed contexts; the ABM should serve as a generic model that can be applied to various context of farm interactions.

The interactions important for each network vary across the 7 networks, and thus the modelling framework needs to consider all possible interactions. Because of the diversity of the networks, it was not possible to develop a one-size-fits-all model and, at the same time, it was not feasible, in the time allocated, to develop different models for the different situations. In **this version of the model**, we chose to build a conceptual model that includes the productions systems most represented, i.e. beef cattle, cereals and cash crops. **Farm interactions** are interpreted as direct exchanges of manure and livestock feed. Only distances between farms are taken into account for the spatial component. We do not include temporal trade-offs, i.e. all products are available at the same time, and there is no delay due to unmatched agricultural production agendas. Regarding farm interactions: we assume that they occur directly from one farmer to another, with no intermediary. Social networks with irrational and asymmetrical point of views are important in determining if farmers will interact. Resilience toward production hazard will be tested (e.g.. lack/excess of products); this can proxy a climatic event, or even price volatility (e.g. if prices are low, there could be an excess of products available).

3 Overview of the model

3.1 Purpose and patterns

3.1.1 Purpose

Following the suggested purposes by Edmonds et al. (2019), with this model, we aim to **describe** how farm interactions occur within mixed landscapes, in order to define what is important for these systems in terms of resilience (farm and landscape resilience). We also aim to check on the **theoretical hypothesis** that the more interactions between farms, the more resilient the system is. The model is built to compare *'what-if'* scenarios of diverse farm decisions regarding interactions with other farms within a given mixed landscape (which configuration of farm interactions show a better resilience in a given landscape for a given *'what-if'* scenario).

The **high-level purpose** of this model is to understand how farm connectivity between farms in a mixed landscape changes farm and/or landscape resilience towards given hazards. Our **specific purpose** is to test whether specific farm networks (issued from farm interactions) within a mixed landscape improve farm and/or landscape resilience.
We define:

- **mixed landscape** as a set of different farms with different productions within a landscape
- **farm interactions** as flows of material (fodder, manure) between farms
- **farm network** as the connections that results from farm interactions; it can be assessed in terms of total number of farms connected, intensity of the connections (how much matter is flowing within a year), etc.

3.1.2 Patterns

Patterns are criteria that are observable from the model's simulations and are important for the model's purpose. In our model, patterns are the following: matter flows and balances (at farm and landscape levels) and network relations (number, intensity)

These patterns will be affected by hazards (climatic, prices) and their response will inform the characterization of resilience.

3.2 Entities, state variables and scales

In the model, all entities are called agents: these include cognitive agents, i.e. agents that make their own decisions, and passive agents, i.e. agents driven by internal processes. Five entities are represented: farm, livestock herd, plot, product and farming area. They are further detailed along with the relationships between them in Figure 1, and in the following sections. The farm is the only cognitive agent in the model. It includes the head/manager that makes decisions and farm structure (agricultural area, animals, labour, etc.). Livestock herd and plot (i.e. agricultural plot) agents are owned and managed by farmers. They create products that are managed by the farm. Farm, livestock herd and plot agents are located within a farming area (specific agro-pedo-climatic conditions).

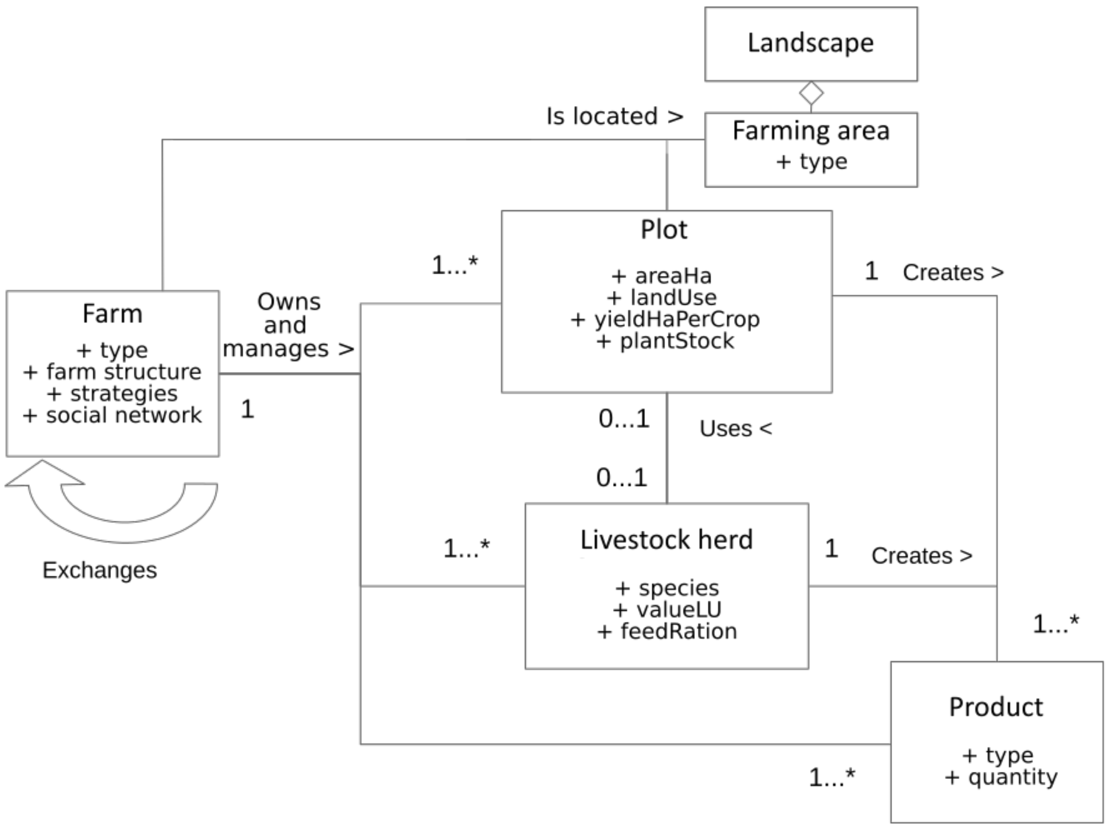

Figure 1: Class diagram: entities of the model with relations among them and attributes.

A class diagram is part of the Unified Modeling Language (UML). It represents the agents of the model (boxes) and their parameters. It 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. A plot agent can be used by a livestock herd agent or none, when the reverse is also possible (e.g. the livestock herd agent does not graze).

3.2.1 Spatial units

3.2.1.1 Farming area, landscape and spatial scale

The farming area agent is a passive agent that represents a territory and its geographical boundaries. Farming area agents can differ according to a type, which relates mainly to agro-pedo-climatic conditions (see Table 4). The spatial extent of the model (landscape boundary) is defined by the aggregation of farming area agents, which are contiguous. Here, at most, the spatial extent reaches the size of a NUTS3 region (Nomenclature of Territorial Units of Statistics), i.e. the size of our study area.

Table 4: Parameters and variables for farming area entity. Dml = dimensionless

Dimension	**Name**	**Description**	**Type**	**Unit**	**Range/Values**	**Changes**
Structure	type	Type depending on agro-pedo-climatic conditions	string	dml	Set of 'farming area types'	static

3.2.1.2 Plot

The plot agent represents a portion of land where agricultural production takes place. Concerned parameters relate to the farm that manages them, their production and resources (see Table 5). In this model, plot agents do not have a shape and are not spatially-explicit. They are located where their owner (a farm agent) is located. Each plot has a land use that can be, for instance: cereals, industrial crops, meadows. Depending on the land use, live vegetation is produced and at some point, can be harvested as a product (see section 5.3 sub models). Yields for each crop and given products are known for each plot as well as the current stock of live biomass (mostly concerned with grazing). A plot agent can host a grazing livestock herd Figure 1.

Table 5: Parameters and variables for plot entity

Name	**Description**	**Type**	**Unit**	**Range/Values**	**Changes**
ID					
ID	Plot id	string	dml	Set of plot	static
myAreaHa	Area of the plot	float	ha	>0	static
Management					
myOwner	Owner and manager of the plot	farm	dml	Set of farm	static
Production					
landUse	Land use of the plot	string	dml	Set of land uses	annually
yieldHaPerCrop	Last yields the plot reached for each crop	map<string = crop, float = yield>	kgFM/year	<Set of 'crops', see crop yields>	annually
Stocks					
plantStock	Stock of live vegetation biomass	map<string = product, float = quantity>	kgFM	0-*	time step

3.2.2 Farm

The farm agent is equivalent to the farm head/manager and the farm structure. Its main parameters relate to its structure, resources and social network (see Table 6). Regarding its structure, it is located within a farming area with its plots and livestock herds. Each farm agent has a farm type defined according to the European standards for agricultural holdings Commission Delegated Regulation (EU) (2014). This classification distinguishes: specialist holdings (crops, grazing livestock, granivores) and mixed holdings (mixed cropping, mixed livestock, crop-livestock).

Each farm agent, according to its type, owns and manages at least one plot and can own one or more livestock herd agents. They manage the products that are created by the agricultural production. More information on the possible actions of management is available in the sub models section (5.3).

Each farm agent is involved in a social network, constituted of the other farm agents. Farm agents rate each other with a trust parameter that can evolve asymmetrically during the simulation. Each interaction with another farmer is also kept in memory, which is used to update the trust parameter.

Table 6: Parameters and variables for farm entity

Name	**Description**	**Type**	**Unit**	**Range/Values**	**Changes**
Structure					
ID	Farmer name	string	dml	Set of farm	static
headOffice	Point where the head office is located	integer	dml	Set of values within the farming area	static
type	Typology for agricultural holdings	string	dml	Set of farm 'type'	static
Resource					
myPlots	Plots owned and managed by the farmer	list<plot>	dml	Set of plot	static
myHerds	Livestock herds managed by the farmer	list<livestockHerd>	dml	None or set of livestockHerd	static
myProducts	Products managed by the farm	list<product>	dml	Set of product	
Network					
trustNetwork	List of other farmers and trust attribute for each	map<farm, integer = trust value>	dml	<Set of farm, 0-1>	time step
exchangeNetwork	Network and weight according to past exchanges	map<farm, map<string = product, float = quantity>	FM	<Set of farm, <set of products, 0-*>>	time step

3.2.3 Passive agents

3.2.3.1 Livestock herd

Livestock herd is an agent composed of a single species and represents the herd as a whole. The management and feed rationing are activities that apply individually to each agent (see Table 7). The number of animals within the herd is defined in livestock units (LU), allowing comparisons between species. According to Eurostat (2020), “one LU is the grazing equivalent of one adult dairy cow producing 3 000 kg of milk annually, without additional concentrated foodstuffs”. A livestock herd agent is attributed a feed ration by the farm agent that owns them. It is used to define the quantity of feed product they need (see section 5.3 sub models for more details).

Table 7: Parameters and variables for livestock herd entity

Name	Description	Type	Unit	Range/Values	Changes
myOwner	Farm that owns and manages the herd	farm	dml	Set of farm	static
mySpecies	Species of the herd	string	dml	Bovine	static
valueLU	Number of animals in the herd	float	livestock unit (LU)	0-*	static
feedRation	Type of feed ration and quantity needed	map<product, float = quantity>	kgFM	>0	time step

3.2.3.2 Product

Product is a passive agent created by a livestock herd (e.g. manure) or a plot (e.g. forage) agent. It is defined by a type depending on what is made of and a quantity (see Table 8).

Table 8: Parameters and variables for product entity

Name	Description	Type	Unit	Range/Values	Changes
myOwner	Farm that owns and manages the herd	farm	dml	Set of farm	static
type	Type of the product	string	dml	Set of product types	static
quantitykgFM	Quantity of the product	float	kgFM	>0	time step

3.2.4 Temporal scale

The model is time-discrete, with a one-year time step, i.e. we assume that between each step, all model processes represent a series of events occurring within one year. We assume that all interactions between farm agents are planned and are happening at once. This implies that we consider that there is no temporal mismatch that would affect exchanges among farms (e.g. a need for a product that is not yet available). This assumption is drawn from our knowledge of the networks (see section **2.4**). Simulations are built on a time horizon between 10 to 20 years. We assume that this will be sufficient in time for social interactions between to take place without having to take into account the lifetime of the farm and succession planning.

3.3 Process overview and scheduling

In this model, processes are either equivalent to farming activities driven by farm agents (i.e. as a result of a decision by the farmer) or agricultural biophysical processes (e.g. vegetation growth, livestock excretion) related to production. Figure 2 is the model activity diagram which shows the order in which each process is executed. This scheduling is sequential: processes happen for all concerned agents before another process takes place.

First, farm agents engage in crop activities: computing manure needs, exchanging/trading manure and managing their plot (e.g. fertilization, harvest). Between crop fertilization and crop harvest, the biophysical process of vegetation growth occurs. Second, all farm agents engage in activities related to livestock production. That is, for livestock owners, computing the amount of feed and fodder they need. The next step is for all farm agents needing feed and fodder or having a surplus, to engage in exchanges with other farm agents. The livestock owners then feed their animals. The latter excrete and produce manure that will be available for the following step.

This order of execution (crop then livestock management) is arbitrary. However, as it represents farm activities within a year, and this forms a cycle, we assume that it does not impact the simulations.

Most processes are specific to an individual farm and thus do not directly impact on other farms. Exchange/trade are the only processes that involve direct and indirect interactions between agents during the process. These flows of manure and forage happen between farms and can imply trade-off for resources during the interaction phase of the simulation. We provide more details on that process in the submodels section (5.3). In order to avoid bias arising from execution order, of these processes, farm agents take actions in a randomized order.

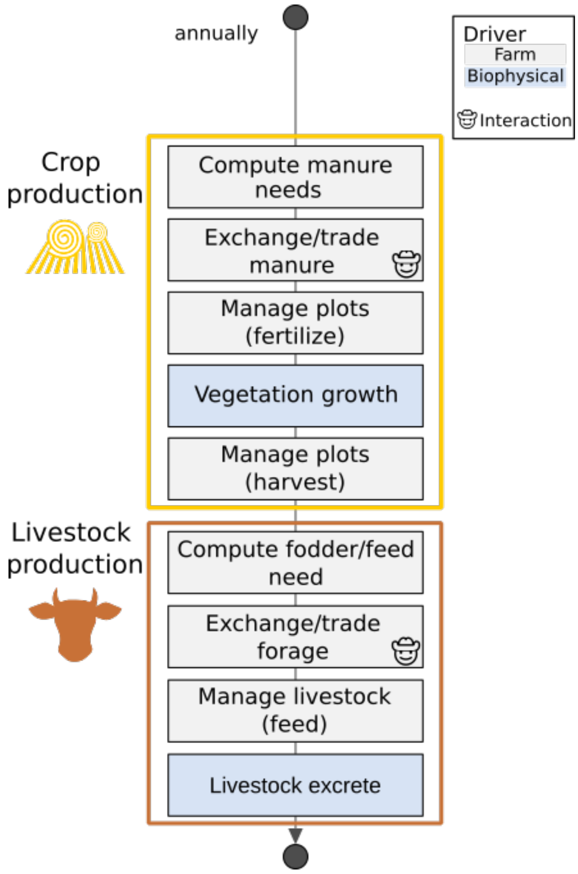

Figure 2: Activity diagram (annual time step).

The first frame (in yellow) highlights crop-related activities, and the second one (brown) highlights livestock-related activities. Grey activities are driven by farm agents, and blue activities are biophysical processes. All these are the processes considered relevant for our modelling purpose. Interactions are between the farmer and other farmers.

4 Design concepts of the model

Basic principles

According to the typology of decision models produced by An (2012), our model is based on heuristic rules deduced from real-world strategies that can be derived from empirical data and observations. Our model is based on literature and will be fine-tuned with empirical data that are not yet available.

Schlüter et al. (2017) frames the diversity of behavioural theories that are used to model social-ecological systems. In our case, we model farm strategies. As we focus on farm interactions and how farmers exchange agricultural products, our conceptual system has similarities with what is developed for industrial symbiosis studies. In these studies, operators self-organize to optimize the use of local resources (Chahla et Zoughaib, 2019 ; Ghali et al., 2017 ; Lange et al., 2021; Romero et Ruiz, 2014). In these studies, the theory of planned behaviour from environmental psychology is widely used. This theory aims at predicting behavioural intention by taking into account the attitude (values and beliefs), subjective norm (what he thinks is socially accepted or not) and perceived behavioural control (what he can really do) of the decision-maker.

We base our model for decision-making on an adaptation of this theory. The attitude is mainly defined by the notion of trust, in which the farm agent has beliefs about the functioning of its interactions (e.g. honesty, implied reciprocity). We assume a social norm in the model that forces all farm agents to exchange with each other if they can, rather than exchanging out of the network. Perception of control is replaced by the limitations induced by the context, e.g. distances between farms implying too high a cost.

Emergence

The key outcomes of the model are networks linking farm agents as a result of their interactions. These interactions emerge from how farm agents respond to multiple factors that are dependent on the farm and environment (e.g. implying more or less production, distance to another farm, etc.). Flows of matter from and to farms are, to a lesser extent, emerging from the model as farm structure induces the need to import/export products.

Adaptation

Farm agents adapt their interactions with other farm agents, depending on their resources (fodder/feed and manure) and the resources owned by the others. They tend to reach their specific objectives by following *if-then* rules that reproduce observed behaviours.

Objectives

Each farm agent aims to get enough fodder/feed for its livestock herd and enough manure for its crops. The algorithm is described in the sub models section (5.3).

Learning

Learning is not included as such in the model. However, through the fact that farm agents remember their past interactions with others, they will prioritize their exchange with someone they exchanged with in the past.

Prediction

Farm agents make their decisions according to the current situation. They do not predict future conditions.

Sensing

Here we consider a small network of farms. We assume that farms have access to the information about all other farms that would be in excess or in need of a product. From that knowledge they can interact with the other farms and get the accurate value of the excess/need. Farm agents assign an asymmetrical rating to other farm agents.

Interaction

Interactions are direct and indirect. They occur between farm agent when one agent needs a product and another has an excess of it. In that case they can directly interact and exchange the product. This creates indirect interactions with all others farm agents as they might be impacted by the fact that the resource has been exchanged and therefore less is available.

Stochasticity

Stochasticity is included at the initialization of the model. Farm agents are distributed randomly within the landscape, according to their type. This implies varying distances between farm agents from one simulation to another. Total farming area and livestock units are attributed to farm agents according to their type, within a range of possible values.

During the simulation, stochasticity is used to set the climate, which is drawn randomly (dry, average, rainy). Crop production is then impacted as crop yields vary depending on the climate (see 5.3 submodels section).

Collectives

No collectives such as social groups are included in the model. They may emerge from the model simulation but will not affect it.

Observation

At each step, we observe for each farm agent, its need for each product and if the demand for the product is satisfied. We also observe the matter flows that come in and out of the farm, as well as the origin and destination of the flow (other farm name). This allows the computation of farm level balances and social networks.

5 Details of the model

5.1 Initialization

Figure 3 represents the activity diagram of the initialization of the model. First farming area agents are created. Their shape depends on the studied network. Farm agents are then initialized. Their number and types are fixed, which is dependent on the network studied. Plot and livestock herd agents are created according to each farm agent parameter.

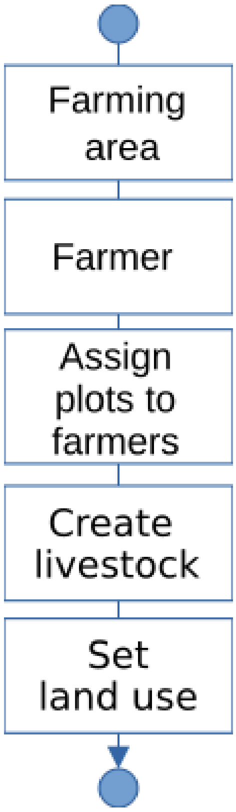

Figure 3: Activity diagram of model initialization

5.2 Input Data: example from the French network

Landscape: For France, we use the shape of the French NUTS3 area called Ariège (n°FRJ21). As shown on Figure 4, three possible types of farming areas are distinguished mainly due to topography: piedmont (>900m), hillsides-plain (<500m) and intermediary (500-900m).

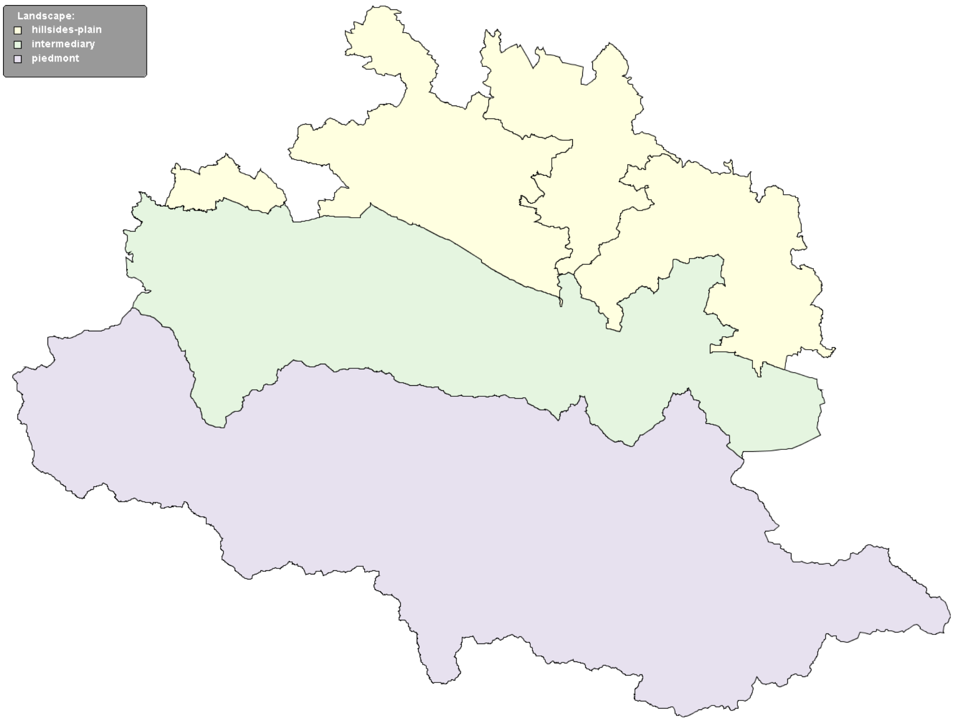

Figure 4: Example of landscape and farming areas for the French network (Ariège)

Farm initialization: Table 9 is an example from the French network of the information required to initialize farm agents. This includes data on the location of the farms, crop grown and livestock numbers. The French network is constituted of 16 farms.

Table 9: Data for farm initialization for the French network

Farm type	Number of farm agents	Location	Area (ha)	Livestock herd (LU)
Crop	8	Hillsides-plain	Cereals: 55-75 ha Protein crops: 20-30 ha Grassland: 0 ha	0
Crop-livestock	6	Intermediary	Cereals: 70 ha Protein crops: 10 ha Grassland: 70 ha	40
Livestock	4	Piedmont	Cereals: 0 ha Protein crops: 0 ha Grassland: 60 ha	60

5.3 Submodels

5.3.1 Product management and interactions with other farms

The farm agents decide what they will do with their products. As shown in Figure 5, they can either: use the product on their own farm or sell it to another farm if they have excess. If they have insufficient product, they will purchase it from another farm. In this model, farm agents do not plan product storage. If any product owned by the farm is available in surplus, it will be available for other farm agents to buy. The quantity of product stocked by the farm agent is dependent on the quantity of surplus they did not sell. There is no economic constraint included in the model, i.e. the selling and purchasing activities relate to exchanges, and costs are not associated with these exchanges.

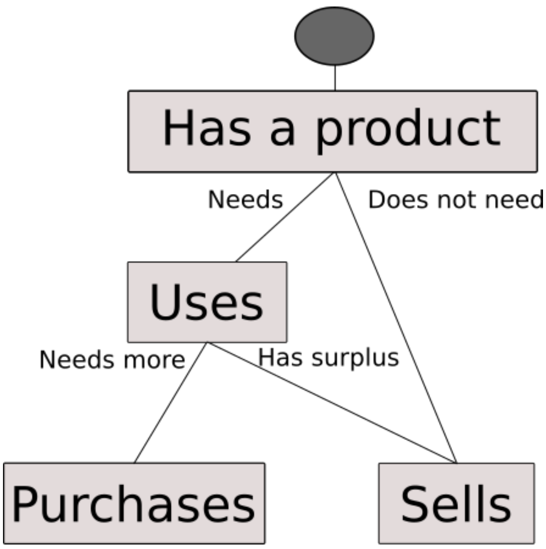

Figure 5: Farm agent decision tree to decide what to do with a product

5.3.1.1 Interactions with other farms

Here, farm interactions are understood as exchanges of products with no cost and which do not have to be reciprocated.

In order to solve farm interactions, we base our algorithm on a matching problems algorithm. This algorithm aims to find a match between two kinds of populations. In our case, we have farm agents that want to purchase a product (buyers) and farm agents that sell it (salespersons). Multiple versions of matching problems exist. In our case, matching farm agents by pairs, as in the stable marriage problem (also known as Gale-Shapley algorithm), is not suitable. We might need to match one individual with many others. For instance, when one farm agent has a greater need for a product than can be met by one farm agent, the first can interact with more than one farm agent to fulfil its requirements. Our case is closer to “college admission” problems where students are matched with colleges. In this case, 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, buyers apply for an interaction of the wanted product with their top-ranked salespersons, who in turn check on their top list and decide if they will accept the proposed interaction (see Figure 6). If a buyer still requires more product after the interaction, he can ask another salesperson. The resolution of the problem might depend on whom starts asking to whom (buyers or salespersons).

Each farm agent rates the other farm agents. This rating is dependent on their behaviour (e.g. spatial proximity, trust in others, etc.).

- It is possible to have a different rating for a same farm agent if they sell or buy a different product. Each rating depends on the farm agent that does the ranking, i.e. it can be asymmetrical.
- It is possible to have a threshold (minRate) that fixes that under a certain rate, the farm agent will not trade with a farm agent rated below this threshold.

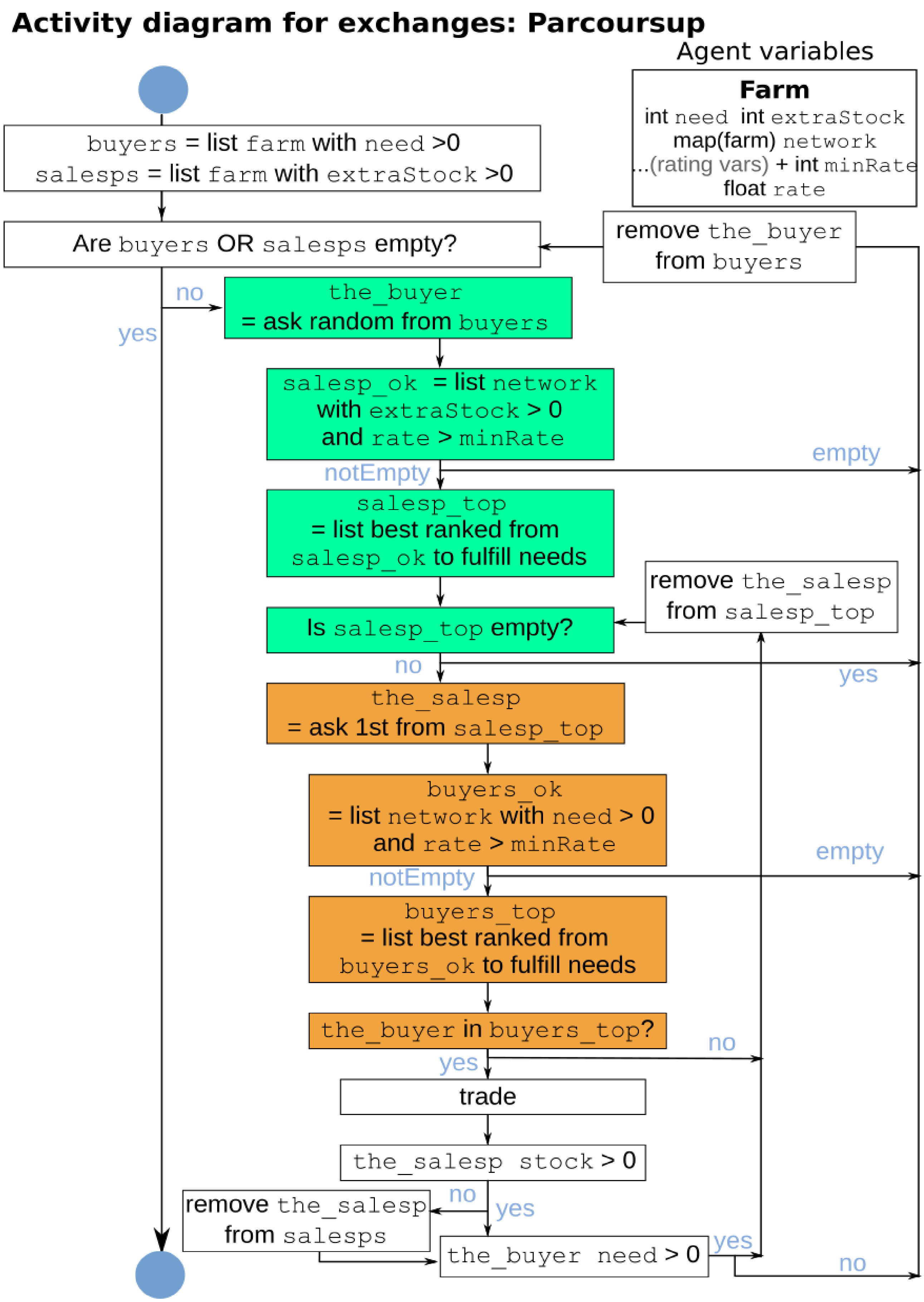

Figure 6: *Farm interactions algorithm*

5.3.2 Vegetal products according to possible land uses

All land uses relate to agricultural land. Vegetation growth is computed according to a nominal yield (see Table 10) for an example from the French network).

Table 10: Possible products and yields for each land uses

Type	Crop	Product	Product yield (kgFM/ha)	Co-Product	Co-product yield (kgFM/ha)
Crop	Cereals	Grain	6500	Straw	6500
	Protein crops	Grain	2500	-	-
Forage	Grassland	Hay	4300	-	-

The impact of climate on the yields are:

- dry: 75% of the product yield
- average: 100% of the product yield
- rainy: 125% of the product yield

Even though we take into account cropping practices such a crop fertilization, it has no effect on the yields. We assume that if the farm agent does not have enough manure, it will always be able to buy it (or another type of fertilizer) from an external market, as economic limitations are not included in this version of the model.

5.3.3 Crop practices

In this model, only fertilization with manure is included. The need for manure depends on the land use and area of the plot, and is calculated, for each plot agent, as:

manure_required (kgFM/year) = $need_i$ x area plot

with

- *need* being the quantity required for 1ha,
- *i* being the land use,
- *area* being the area of the plot (ha).

Table 11 is an example of the manure required for each crop type for the French network.

Table 11: Fertilizer requirement for each land use

Land use \ Fertilizer type	Manure (kg FM/ha)
Cereal	3000
Protein crops	2000
Grassland	0

5.3.4 Livestock feeding

For each livestock herd agent, a feeding system is defined according to the type of the farm agent that owns it, i.e. a quantity of cereals, protein crop and hay required for the herd. Feeding systems are fixed at the initialization stage. The total quantity of each product required each year is calculated as follow:

$quantity_i$ (kgFM/year) = ration $quantity_i$ x value_LU x 365

with

- *ration quantity* being the quantity needed for 1 LU/day,
- *i* being the product,
- *value_LU*, the number of LU within the herd.

A diversity of feeding systems can in the model, depending on the feeding practices of the networks. Table 12 shows an example of feeding system based on the French network: a system based on local products, with soybean meal replaced by protein crops such as pea or faba bean.

Table 12: Feeding system for livestock herd: application with the French network

Ration	Cereals (kg FM/day)	Protein crop (kg FM/day)	Hay (kg FM/day)
Beef cattle (per LU)	3	2	15

In addition, depending on the system, a livestock herd might require straw. This requirement is computed as follows:

quantity_straw (kgFM/year) = need_straw x value_LU x nb_of_days_in_the_building

with

- *need_straw* being the need for straw (kg FM/LU/day),
- *nb_of_days_in_the_building* being the number of days the herd remains in the building,
- *value_LU*, the number of LU within the herd.

For the French network and beef cattle system, need_straw equals 7kgFM/LU/day and animals stay all year in-barn.

5.3.5 Manure production

Manure production depends on the type of farming system, the feeding system and the type of housing. For the French beef cattle system, we assume of 15 to 30 kgFM/LU/day of manure is produced. The value is set randomly at initialization. This considers the high variation that is observed from the network, depending on the housing.

6 Conclusion

In summary, we have built an agent-based model which represents farm interactions within a mixed landscape. These interactions take place when farmers exchange agricultural products with each other. This report describes the modelling framework focused on direct exchanges of manure and livestock feed, which will be implemented using Gama (http://gama-platform.org/): a multi-agent simulation and spatially explicit modelling platform (Taillandier et al., 2019). More information on the networks to be simulated will be required, in order to fine-tune and parametrize the model. Particularly, getting to know origins and destinations of farms' inputs and outputs: what is produced for interanlconsumption and what is imported from/exported to another farm or another stakeholder. This data will be collected during data collection campaign of T2.3. Simulations will be used to understand how connectivity between farms in a mixed landscape changes farm and/or landscape resilience in response to the hazards of climate change. This conceptual model can be used as a basis for models that describe more complex interactions (e.g. land exchanges, agroforestery), as long as the corresponding data to describe the processes is collected.

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